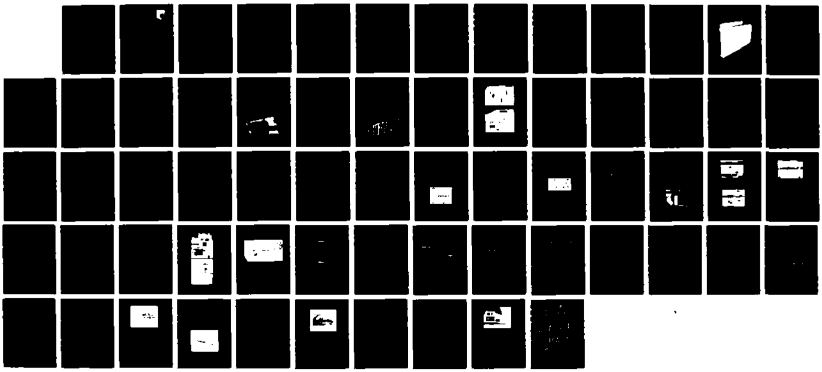
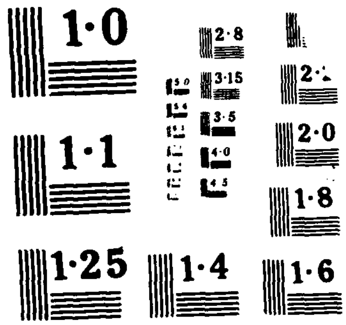
AD-A190 990 NONDESTRUCTIVE EVALUATION OF LARGE SCALE COMPOSITE COMPONENTS(U) MCDONNELL AIRCRAFT CO ST LOUIS MO D C KING ET AL. JAN 88 AFWAL-TR-87-4116 1/1

UNCLASSIFIED F33615-84-C-5017 F/G 11/4 NL




1·0
1·1
1·25
1·4
1·6
1·8
2·0
2·8
3·15
3·5
4·0
4·5

DTIC FILE COPY

(2)

AFWAL-TR-87-4116

AD-A190 998

NONDESTRUCTIVE EVALUATION OF LARGE SCALE COMPOSITE COMPONENTS

D.C. KING
R.D. LAWSON
B.J. ROMINE

McDonnell Douglas Corporation
McDonnell Aircraft Company
P.O. Box 516
St. Louis, MO 63166

January 1988

Final Report for Period September 1984 - March 1987

Approved for Public Release; Distribution Is Unlimited

MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533

88 2 2 084

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder, or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

James A. Holloway

JAMES A. HOLLOWAY
Nondestructive Evaluation Branch
Metals and Ceramics Division

FOR THE COMMANDER

D. M. FORNEY, JR., Chief
Nondestructive Evaluation Branch
Metals and Ceramics Division

If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/MLLP, Wright-Patterson AFB, OH 45433-6533 to help us maintain a current mailing list.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE A190998

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for Public Release: Distribution is Unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFWAL-TR-87-4116
6a. NAME OF PERFORMING ORGANIZATION McDonnell Douglas Corp. McDonnell Aircraft Company 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Wright Aeronautical Laboratories Materials Laboratory (AFWAL/MLLP)
6c. ADDRESS (City, State, and ZIP Code) P. O. Box 516 St. Louis, MO 63166	7b. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB OH 45433-6533
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F33615-84-C-5017
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. 62102F PROJECT NO. 2418 TASK NO 02 WORK UNIT ACCESSION NO. 22

11. TITLE (Include Security Classification)
Nondestructive Evaluation of Large Scale Composite Components

12. PERSONAL AUTHOR(S)
D. C. King, R. D. Lawson, B. J. Romine

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 9-84 TO 3-87	January 1988	66

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
14	02	
11	04	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Ultrasonic Testing,
Large Area Scanner,
Composite Materials

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report covers the development of a reciprocating time-of-flight ultrasonic inspection system capable of rapid scanning on large area composite structures. Representative aircraft composite structures with flaw inclusions were fabricated to evaluate the effects of scanner design, coupling characteristics, part curvature, near and far surface defect detection, imaging, and data acquisition and storage capabilities. The results were used to combine a mechanical scanner, software, and electronic equipment into a working breadboard system. Breadboard evaluation results indicate that a downsized portable system is a viable inspection tool, and produces production quality ultrasonic C-scan images at comparable production scanning rates.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Uncalssified
22a. NAME OF RESPONSIBLE INDIVIDUAL J. Holloway	22b. TELEPHONE (Include Area Code) 513-255-9802 22c. OFFICE SYMBOL AFWAL/MLLP

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

FOREWORD

This final technical report covers the work performed under United States Air Force Contract F33615-84-C-5017, "Nondestructive Evaluation of Large Scale Composite Components", 25 September 1984 to 31 March 1987. This program has been administered under the technical direction of Mr. J. A. Holloway, AFWAL/MLLP, Nondestructive Evaluation Branch, Wright-Patterson Air Force Base, Ohio 45433.

McDonnell Aircraft Company (MCAIR), St. Louis, Missouri is the contractor. Mr. Byron A. Davis is the program manager. Mr. Thomas S. Jones served as the principal investigator until February 1987 when Mr. Daniel C. King assumed that position.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

1.0 INTRODUCTION

1.1 BACKGROUND

Advanced laminated composite structures have seen increasing application in aerospace structures over the past 20 years. Initially they were substituted for the aluminum skins on airframe control surfaces. The excellent service history of these structures has brought increasingly wide and critical application of composites in primary aircraft structure. Composites are now used in critical wing and fuselage applications as well as in control surfaces and secondary structures. Composites applications have gone from less than 1 percent of the structural weight for early applications to over 26 percent on the AV-8B. Next generation aircraft are expected to have even greater amounts of composite application. Also, the application of these materials has extended from the small, high-performance fighter aircraft to larger bomber and transport aircraft. As this trend continues, the surface area of airframe structure made with laminated composites will become extremely large.

While laminated composites have had a very good performance history, they can be damaged. Perhaps the most troublesome source of damage is low velocity impact damage. Laminated composites can withstand substantial impact; however, they typically show little or no visible indication when they do experience damage.[1] While manual inspection methods are available to detect this type of damage, the ultrasonic signals produced by the materials are new to many inspectors, and they can be difficult to interpret. Also, the time required to evaluate a large structure could be prohibitive.

The application of advanced composites to continually larger and more critical aircraft structure is, then, presenting a potential challenge to the field inspection of these structures. Should a large area composite component require a full part field inspection, the currently available techniques would require a substantial man-hour investment to accomplish the task. Several systems are under development, or have been developed in recent years, which will provide some level of automated data interpretation and recording. Systems such as the Ultra Image III, initially developed by General Dynamics Electric Boat and now marketed by SAIC[2], the ISIS, developed by General Dynamics-Fort Worth under contract with the Air Force[3], the ARIS, under development by Southwest Research Institute through a contract with the Air Force[4], and the PARIS, being developed by Sigma Research under contract with the Navy[5], all provide some measure of improved data collection, interpretation and display, but none are able to collect data at a rate to be suitable for large area inspection. Therefore, a need exists to provide an inspection technology capable of performing this inspection in a very rapid and yet reliable manner.

The NDE of Large Scale Composite Components program was conceived to produce this technology for the field inspection of large composite structures. A target inspection speed of 100 square feet per hour was established as a goal for this inspection technology. The system should require minimal operator skill and training to interpret the results of the inspection.

1.2 TECHNICAL APPROACH

Our approach to this problem was to make extensive use of our experience in the design and use of production composites inspection systems. The Automated Ultrasonic Scanning System (AUSS)[6], was designed at MCAIR to provide a tool for the rapid inspection of high volume composite aircraft components. This was achieved through the use of customized scan plans and automated data processing. Initially, the AUSS operated exclusively in a through-transmission mode. This inspection mode requires access to both sides of the component and is therefore not well adapted to field inspection applications.

More recent versions of the AUSS are able to operate in a pulse-echo inspection mode where access is required to only one surface of the part. The pulse-echo inspection mode is frequently used in the field inspection of composites. Our approach to this program is based on this pulse-echo modification. Under MCAIR IRAD funding, a portable scanning head was produced to interface with AUSS type ultrasonic data processing technology to provide rapid inspection of composites. This system, identified as the Mobile Automated Ultrasonic Scanner (MAUS), was used as a baseline approach for the development of an inspection system to meet the in-service inspection needs. Various approaches were evaluated to provide the inspection, data processing, documentation, and user interface requirements for a large area composite in-service inspection system.

1.3 PROGRAM OVERVIEW

The program was organized in three tasks:

- Task I - Composite Panel Fabrication
- Task II - Ultrasonic Technique Development
- Task III - Prototype Fabrication and Demonstration

Task I called for the design and fabrication of three composite panels. One additional existing panel required only slight modifications to be suitable for use on this program. Two of these panels were designed to provide a vehicle for the evaluation of alternative approaches to the system. They were selected to represent a range of applications which might be encountered by a field inspection system. These panels provide thick and thin laminate sections as well as thickness transition regions. They also present both flat and curved entry surface geometries. The remaining two panels were selected primarily to provide a large inspection surface on which to evaluate the inspection speed and accuracy on large components. The large panels were also selected to present a large variety of design configurations such as thick and thin sections, tapers, curved surfaces, and complex geometries.

In Task II, we investigated the ultrasonic requirements peculiar to the inspections for which the system is to be used. These requirements include details such as the appropriate ultrasonic transducer types, frequencies, bandwidths, and beam profiles which provide the proper combination of near and far surface resolution and penetration of thick laminate sections. We further investigated a variety of approaches to the problem of maintaining and assuring sound beam coupling to the part at the rapid scan rates required by this program. The results of these investigations were used to optimize the design of the breadboard ultrasonic scanning system.

In Task III, we designed and constructed a breadboard prototype of the inspection system based on the ultrasonic concepts developed in Task II using the MAUS. This breadboard electronic and scanner head system was demonstrated to DoD and industry personnel in a final program review on June 18, 1987.

2.0 TECHNICAL PROGRESS

2.1 TASK I - COMPOSITE PANEL FABRICATION

Composite specimens were needed for both the Task II and the Task III efforts. In Task II, the specimens were needed to study the interaction of ultrasound, as it applies to an automated field inspection, with thick and complex configured composite structures, and to validate the inspection approach being developed on realistic components. In Task III, larger composite components were needed to refine and verify the performance capabilities of the system as it would be used in the field.

The majority of the development effort was done using four composite panels, two for Task II and two for Task III. The two panels for the Task II work are a carbon epoxy bulkhead beam panel and a fuselage simulation panel.

The bulkhead beam specimen, Figure 1, contains sections of 0.25 inch, 1.74 inch, and 2.58 inch thickness. The 0.25 inch and the 1.74 inch sections are of sufficient size to evaluate the ultrasonic response differences between thin and thick laminates and to determine the effects of transducer scanning motion on these responses. The 2.58 inch thick section is only slightly over one-half inch wide, and as such, is not completely representative of a large area structure. The narrow width of this section constrains the ultrasonic beam and thereby modifies the normal sound field. This makes the readings of ultrasonic response characteristics in this area somewhat suspect.

The bulkhead beam specimen was modified, as shown in Figure 2, to contain flat bottomed holes. These holes are arranged at a variety of depths to demonstrate the ability of the inspection technique to detect flaws ranging from 0.015 inch below the near surface to 0.005 inch from the far surface in the 0.25 inch thick section, and from 0.24 inch below the front surface to 0.050 inch from the back surface resolution in the thick section. An additional hole at a depth of 2.00 inches is provided in the 2.58 inch thick section. We used this hole to verify the ability of the ultrasonics to detect a reflector at this depth; however, because of the narrow width of this section, we could only evaluate this reflector statically, i.e., with the ultrasonic transducer held still rather than scanning.

In addition to the bulkhead beam panel, which provided us with the capability to study flaw depth effects, we fabricated a panel which simulates composite fuselage structure. The panel has a thin (0.084 inch) skin which is curved to a fuselage moldline and integrally stiffened with cocured hat sections. The panel contains thirteen intentional flaws, produced by placing layers of TFE film in the laminate during layup. The flaws are positioned to represent skin delaminations, skin-to-stiffener disbonds, and delaminations

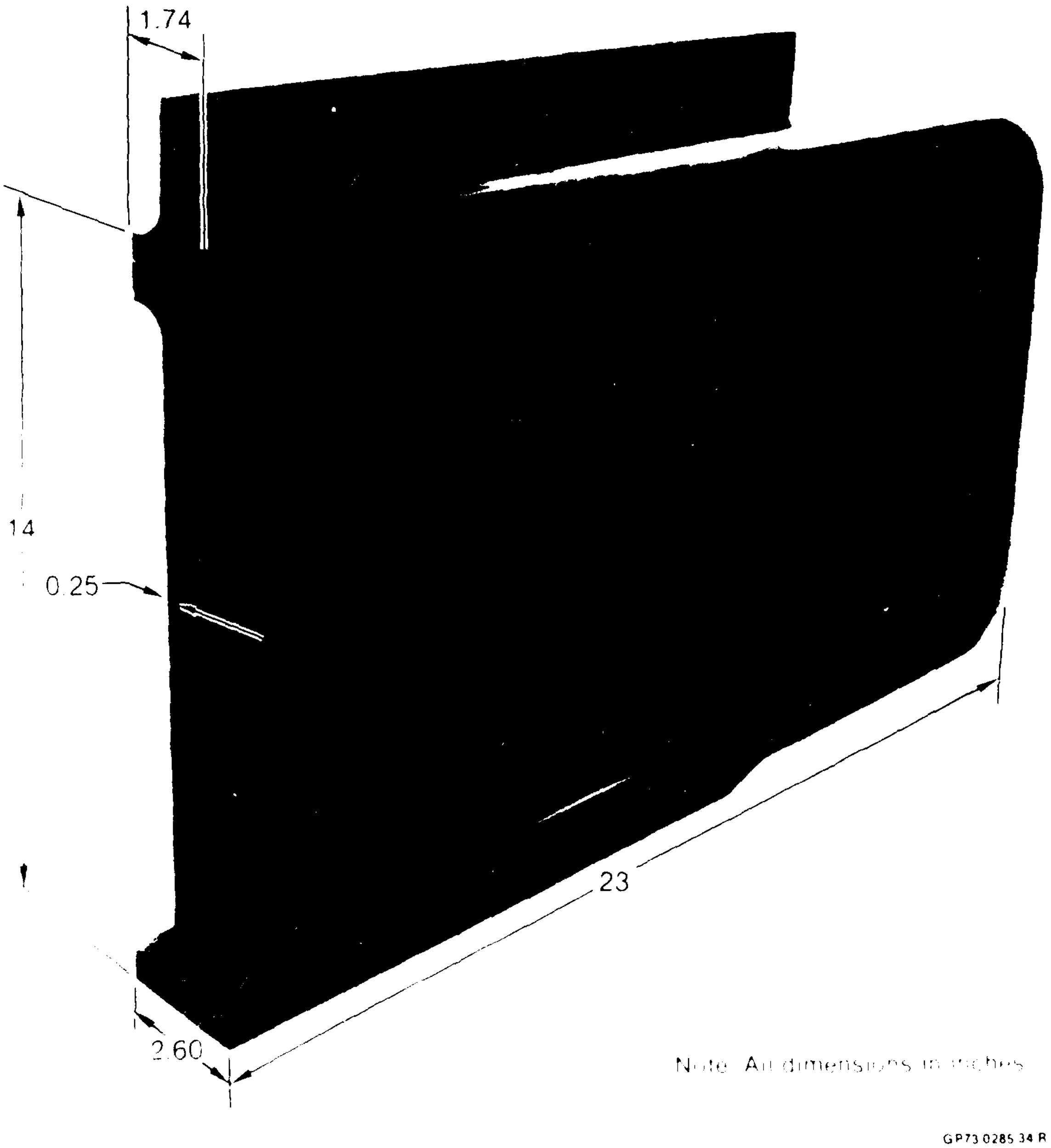


Figure 1. Carbon/Epoxy Bulkhead Beam

Hole Number	Part Thickness	Hole Depth	Remaining Material
1	1.740	0.050	1.690
2	1.740	1.500	0.240
3	1.740	0.250	1.490
4	1.740	1.000	0.740
5	0.250	0.005	0.245
6	0.250	0.010	0.240
7	0.250	0.015	0.235
8	2.584	0.500	2.084
9	0.250	0.230	0.020

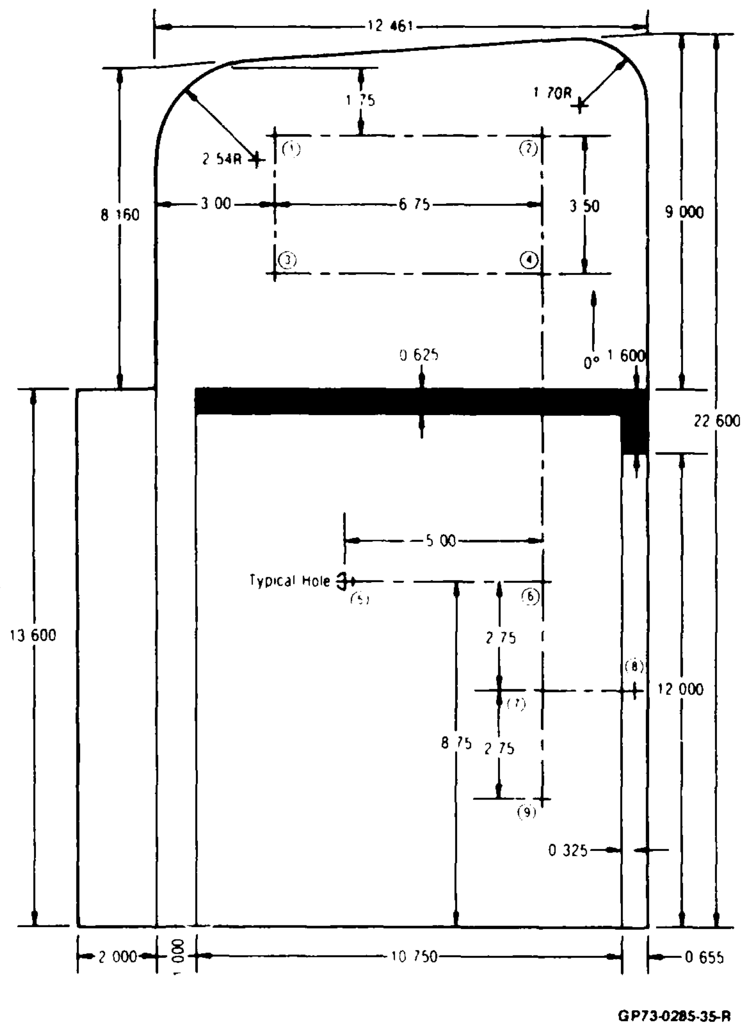
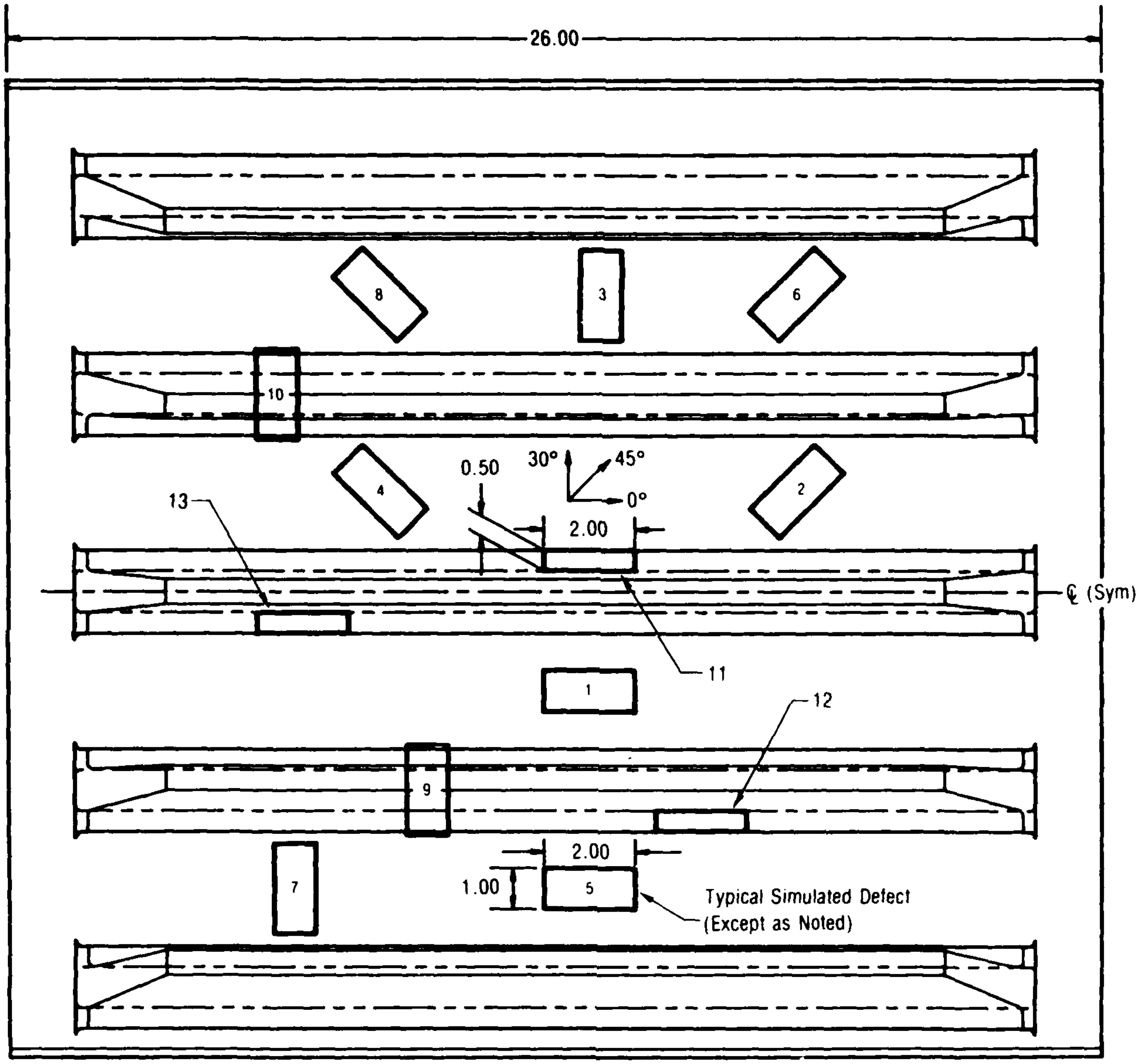


Figure 2. Bulkhead Beam Flaw Locations

within the hat stiffeners. The panel has also been painted to simulate flight hardware. The flaw locations are illustrated in Figure 3. In addition to these two panels, a number of existing specimens were used to evaluate various aspects of the ultrasonic system as will be discussed later in this report.



Simulated Defects

Number	Orientation	Between Plies
	Skin	
1	0	2 - 3
2	+45	2 - 3
3	90	2 - 3
4	−45	3 - 4
5	0	5 - 6
6	+45	5 - 6
7	90	5 - 6
8	−45	4 - 5
9	90	2 - 3
10	90	5 6

	Between Skin and Stiffener (HAT)	
11	0	6 (Skin) - 3 (HAT)
	Stiffener (HAT)	
12	0	6 - 10
13	0	11 - 12

GP73-0285-36-R

Figure 3. Hat Panel Flaw Locations

The larger composite panels used for the Task III demonstration effort consist of a modified F/A-18 Inner Lower Wing Skin and a TAV-8B Forward Fuselage Sidewall Panel. Both of these are actual composite aircraft structure currently in production at MCAIR. These two panels include structure which is flat, curved, tapered, and which includes integrally attached stiffeners. Each specimen contains a large number of simulated flaws, located in a variety of depths and regions. The two large components were fabricated using numerically controlled Gerber cut production ply sets and production tools and techniques. The parts were fabricated in our Advanced Manufacturing Fabrication Facility. This facility has full composite fabrication capabilities and routinely fabricates modified or special purpose articles replicating production hardware. They also evaluate advanced tooling or fabrication processes.

The F/A-18 wing skin was modified to remove the high cost titanium fitting at the root and terminating the composite plies at what would be the edge of the root fitting. This fitting adds substantially to the cost of the component and is not representative of the type of structure addressed in the statement of work. The production part contains two additional step plate fittings at the pylon attachment locations. Rather than include these relatively high cost fittings, we saved the pieces of composite prepreg cut from each ply to make room for these fittings and merely replaced them in the laminate as the part was assembled. This resulted in the laminate being effectively "healed" into a continuous laminate in these areas.

The F/A-18 Inner Lower Wing Skin is basically a flat monolithic laminate which ranges in thickness from approximately 0.36 inch thick to approximately 0.84 inch thick. The thickness changes take place in a large number of ply drop-off regions which form tapers of varying grades. The Wing Skin is fabricated primarily from 10 mil unidirectional AS4/3501-6 carbon epoxy prepreg in a crossplied configuration. The plies are numbered sequentially from the inner (tool) surface outward with ply number 1 being a 0.005 inch thick glass epoxy ply. This ply covers the areas of the part intended to come in contact with the aluminum wing substructure and serves to provide a corrosion barrier. Fifty nonporous Teflon^R coated glass cloth inserts, 1 x 2 inches in size and 0.003 inch thick, were placed throughout the laminate. The insert locations range from 0.01 inch from the outer (inspection) surface to within 0.01 inch of the inner surface. The inserts are located in a wide range of material thicknesses and in tapering regions.

Figure 4 shows the approximate locations of the inserts within the wing skin and Table 1 shows the ply depth location of each insert. The approximate depth below the inspection surface and distance from the back surface are shown for each insert based on nominal cured ply thicknesses. Where flaws are located in tapered regions, a range of thicknesses is given.

The TAV-8B Forward Fuselage Sidewall Panel is highly curved in the forward section as it leads into the nose barrel, and is much more gently curved as it moves back along the side of the cockpit. It has eleven integral hat stiffeners which are cocured to the rather thin carbon epoxy skin. The skin is fabricated from an eight harness satin weave carbon epoxy prepreg cloth and the hats are fabricated from a combination of the cloth and unidirectional tape. All of the inspection areas for this program are of the

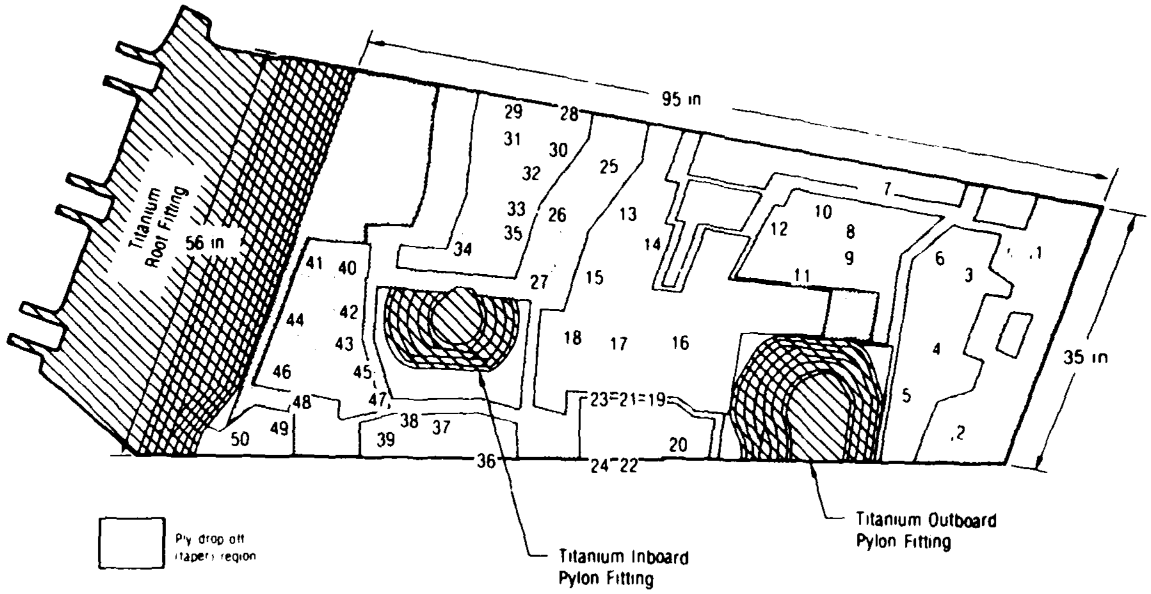


Figure 4. F/A-18 Inner Wing Skin Insert Locations

cloth material since the tape is used exclusively in the top of the hat Stiffeners, which are not ultrasonically accessible from the inspection surface. The skin for this part is relatively uniform in thickness, ranging typically from four to six plies thick, with a few local areas going to as much as nine plies thick. The plies are nominally 0.014 inch thick when cured.

Forty 0.003 inch thick nonporous Teflon^R coated glass cloth inserts were placed throughout the fuselage sidewall panel. The inserts are typically 1 x 2 inches in size and are located at a variety of ply depths within the skin, in the skin-to-hat bondlines, and within the hat flanges. Some of the inserts placed at the skin-to-hat and hat flange locations are 1/2 x 2 inches in size. The TAV-8B version of the sidewall panel is similar to the AV-8B version except that it is about 20 percent larger and contains two additional integral hat stiffeners. The insert locations for the TAV-8B panel are illustrated in Figure 5, and the depths are shown in Table 2. Both the F/A-18 Inner Wing Skin and the TAV-8 Forward Fuselage Sidewall Panel were collated, cured, and inspected using production ultrasonic and X-ray techniques. The results of these tests looked good, confirming the intentional flaws generated by the Teflon^R impregnated glass cloth inclusions. The use of the offal from the machine cut ply set to replace the titanium step splice fittings in the F-18 Wing Skin worked well and from an ultrasonic and visual standpoint, appear to have blended with the surrounding material. The production ultrasonic scan of the F/A-18 Inner Wing Skin is shown in Figure 6. The intentional flaws can be seen as black rectangles in the gray background of the part. Flat areas of the part show up as very light gray or white. Tapers in part thickness show up as medium to fairly dark gray.

TABLE 1. F/A-18 INNER LOWER WING SKIN FLAW PLACEMENT

Flaw Number	Locate on Ply	Depth From OML	Remaining Thickness
1	41	0.239/0.291	0.192/0.255
2	21	0.354/0.385	0.114/0.135
3	81B	0.021	0.338
4	41	0.187	0.171
5	3	0.333	0.026
6	3	0.333	0.021
7	41	0.250/0.281	0.234/0.265
8	15	0.354	0.083
9	3	0.416	0.021
10	7	0.374	0.067
11	21	0.333	0.104
12	5	0.395	0.042
13	81B	0.021	0.458
14	79	0.042	0.437
15	82	0.010	0.468
16	63	0.125	0.354
17	52	0.187	0.291
18	71	0.083	0.395
19	63	0.083	0.312
20	52	0.146	0.255
21	41	0.208	0.187
22	21	0.312	0.088
23	2B	0.385	0.010
24	2B	0.385	0.015
25	63	0.146/0.156	0.478/0.530
26	41	0.322/0.354	0.302/0.333
27	7	0.520/0.645	0.067
28	7	0.770	0.067
29	3	0.811	0.026
30	15	0.686	0.151
31	5	0.790	0.047
32	21	0.624	0.213
33	31	0.520	0.317
34	63	0.208	0.629
35	81B	0.021	0.816
36	79	0.042	0.712
37	71	0.094	0.660
38	52	0.281	0.473
39	41	0.385	0.369
40	21	0.499	0.146
41	31	0.416	0.229
42	15	0.541	0.109
43	41	0.333	0.312
44	52	0.229	0.416
45	63	0.146	0.504
46	5	0.603	0.047
47	71	0.083	0.562
48	52	0.322/0.395	0.135/0.198
49	52	0.094	0.286
50	3	0.354	0.021/0.026

GP73-0285-22-R

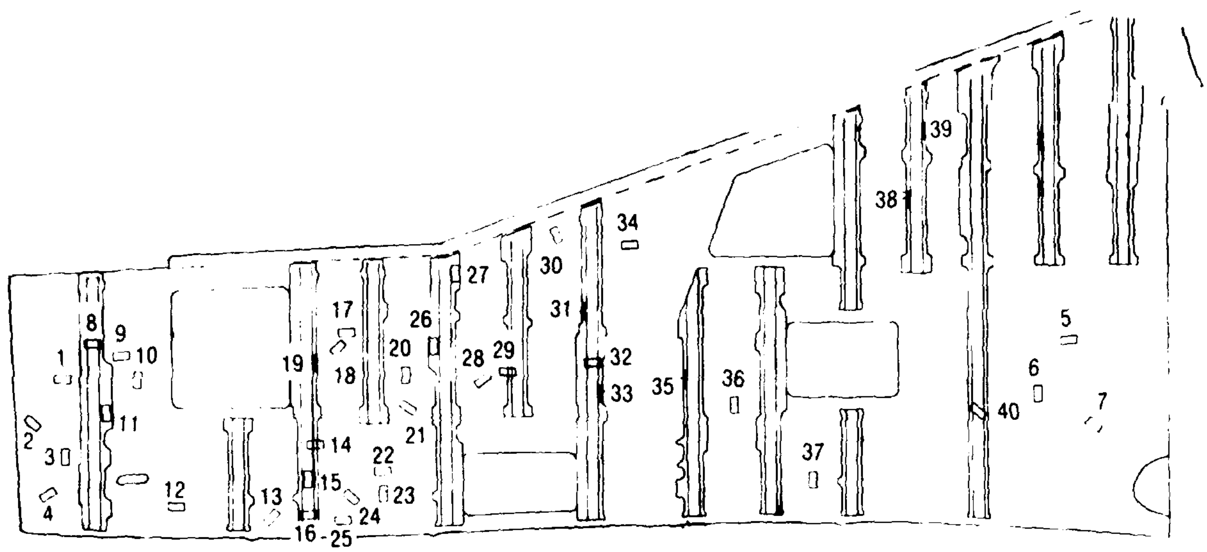


Figure 5. TAV-8B Fuselage Sidewall Insert Locations

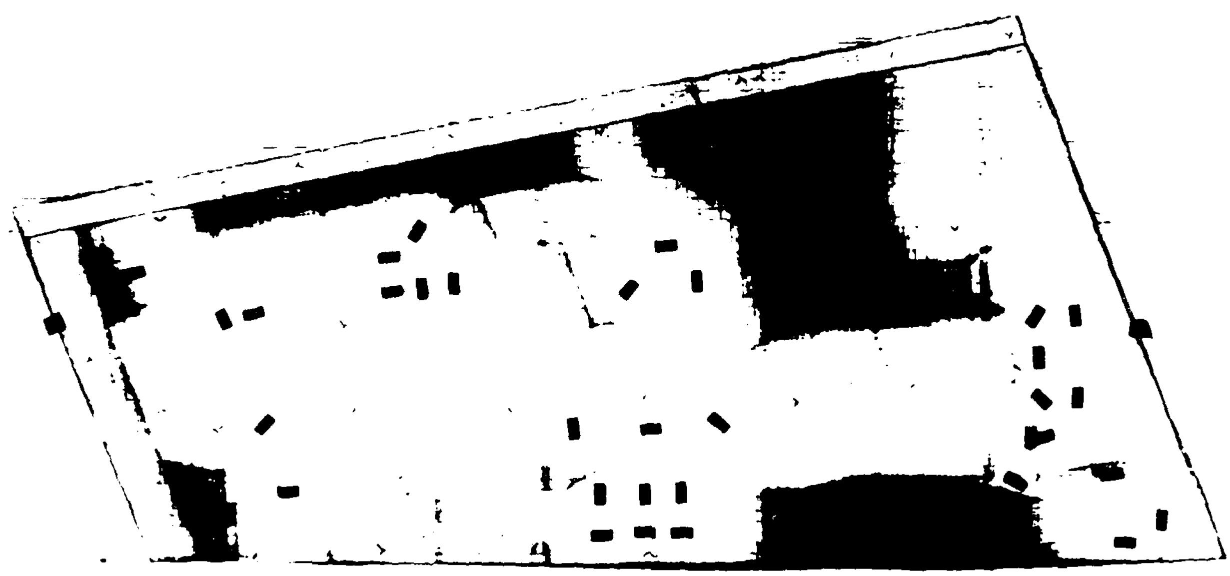


Figure 6. F/A-18 Inner Wing Skin Ultrasonic C-Scan

TABLE 2. AV-8B FORWARD FUSELAGE SIDEWALL PANEL

Flaw Number	Locate on Ply	Depth From OML	Remaining Thickness
1	1	0.014	0.070
2	19	0.028	0.056
3	20	0.042	0.042
4	1	0.014	0.070
5	22	0.056	0.014
6	21	0.042	0.028
7	22	0.056	0.014
8	22	0.056	0.018
9	20	0.084	0.046
10	21	0.098	0.032
11	22	0.112	0.018
12	22	0.042/0.084	0.014
13	23	0.070	0.046
14	19	0.028	0.028/0.084
15	22	0.042	1.128
16	23	0.056	0.014/0.056
17	1	0.014	0.042
18	19	0.028	0.028
19	23	0.056	0.018
20	22	0.042	0.014
21	1	0.014	0.042
22	1	0.014	0.084
23	19	0.042	0.056
24	19	0.028	0.028
25	22	0.042	0.014
26	27	0.112	0.032
27	19	0.070	0.042
28	19	0.028	0.042
29	31	0.126	0.018
30	21	0.042/0.112	0.028
31	23	0.056	0.046
32	22	0.042	0.028/0.060
33	32	0.084	0.018
34	1	0.014	0.042
35	23	0.056	0.018
36	19	0.028	0.028
37	1	0.014	0.084/0.196
38	23	0.084	0.046
39	30	0.112	0.018
40	19	0.070/0.126	0.056

GP73-0285-24-R

The production ultrasonic scan of the TAV-8B panel is shown in Figure 7. All 40 of the flaw inserts were detected by the AUSS ultrasonic inspection, although flaw number 31, which is a 1/2 by 2 inch insert in one of the hat flanges, appears to have folded over and gave a very narrow indication. In addition to the intended flaws, the panel contains two areas of porosity and one area of wrinkled plies. Each of these areas was isolated and did not interfere with the detection of the intentional inserts. They also provided an opportunity to characterize the MAUS response for these conditions. Both of the large panels were painted with standard exterior finish.

2.2 ULTRASONIC TECHNIQUE DEVELOPMENT

Our efforts in this task were concentrated in four areas: (1) the evaluation of approaches to coupling the ultrasound into the part, (2) scanning technique evaluations, (3) ultrasonic transducer development, and (4) panel scan evaluations.

2.2.1 Coupling Technique Evaluations - The selection of a technique for providing coupling of the ultrasound into and out of the parts was a major area of the technique development for this program. Several aspects of the field inspection environment make common and conventional techniques used in production impractical. For example, water immersion or squirter techniques are often impractic l in the field due to lack of suitable water supply or containment system. Also, many conventional contact couplants may not provide adequate coupling on typical in-service finishes.

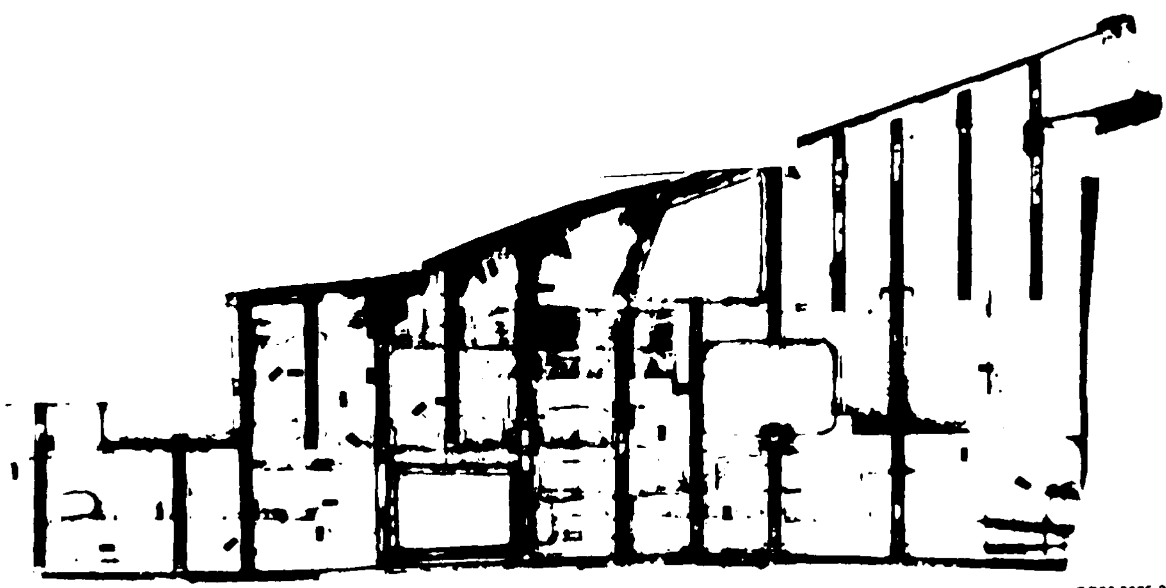


Figure 7. TAV-8 Fuselage Sidewall Ultrasonic C-Scan

The Mobile Automated Ultrasonic Scanner (MAUS) concept relies on the use of four contact transducers to provide the inspection coverage of the part. The MAUS, shown in Figure 8 mechanically drives the four transducers back and forth in the lateral direction while the scan head is manually propelled in a longitudinal direction. The zig-zag path of the transducers is designed to provide full part coverage. However, this scanning pattern results in a nearly constant and fairly rapid relative motion between the transducers and the part surface. This relative motion, and the anticipated part surface condition present some interesting challenges to maintaining a good ultrasonic coupling between the scan head and the part.

Air coupling, that is, using transducers which do not require any liquid couplant, was one solution to many of these problems if adequate resolution and sensitivity could be achieved. For this reason, we evaluated two Ultran search units which are designed to be used for air coupled testing. The search units are identified as WD50, a 4 MHz, 1/2 inch diameter unit, and WD75, a 5 MHz, 3/4 inch diameter unit. These two search units were evaluated on a laminate approximately 0.9 inch thick. The amplitude of the reflection from the back surface of the 0.9 inch thick laminate was monitored. The air coupled transducers produced back echo amplitudes which were generally much lower than for comparable liquid coupled transducers. Further, the echo amplitude was significantly affected by the amount of pressure applied to the transducer normal to the part surface.

Figure 9 shows a plot of the relative signal amplitude of the back surface reflection as a function of the applied normal force for each of the search units. For these tests, the return echo signal was amplified by 40 dB. The amplitude of the pulse applied to the search unit was measured. The amplitude of the back echo was then compared to the applied pulse amplitude to determine the signal loss valued reported in Figure 7, using the following relationship:

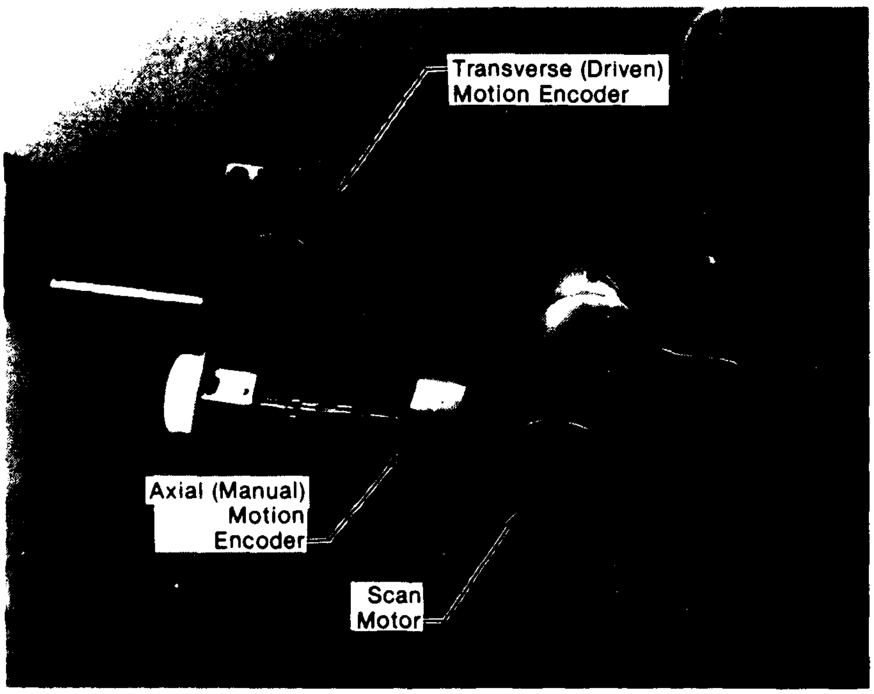
$$\text{Signal (dB)} = 20 \log_{10} \frac{\text{Output}}{\text{Excitation}} - 40 \text{ dB}$$

The signal amplitudes shown in Figure 9 are about 40 dB below the level normally obtainable with conventional transducers. Further, the large variability of the signal amplitude as a function of normal load could prove troublesome on an automated system, particularly with the smaller transducer which, apparently because of the smaller contact area, experienced far greater variability. Though the concept of air coupled transducers is appealing, it appears that the sensitivity of this type of search unit will not be adequate for our large area scanning applications.

2.2.2 Scanning Technique Evaluations

2.2.2.1 Data Collection and Coupling - Since the AUSS data handling system was designed to work with a single channel of ultrasonic data, the use of four channels on the MAUS posed some interesting challenges to the software systems. In the MAUS concept, the transducers are driven in a

GP73-0285-3-R



GP73-0285-4-R

Figure 8. Prototype MAUS Scan Head

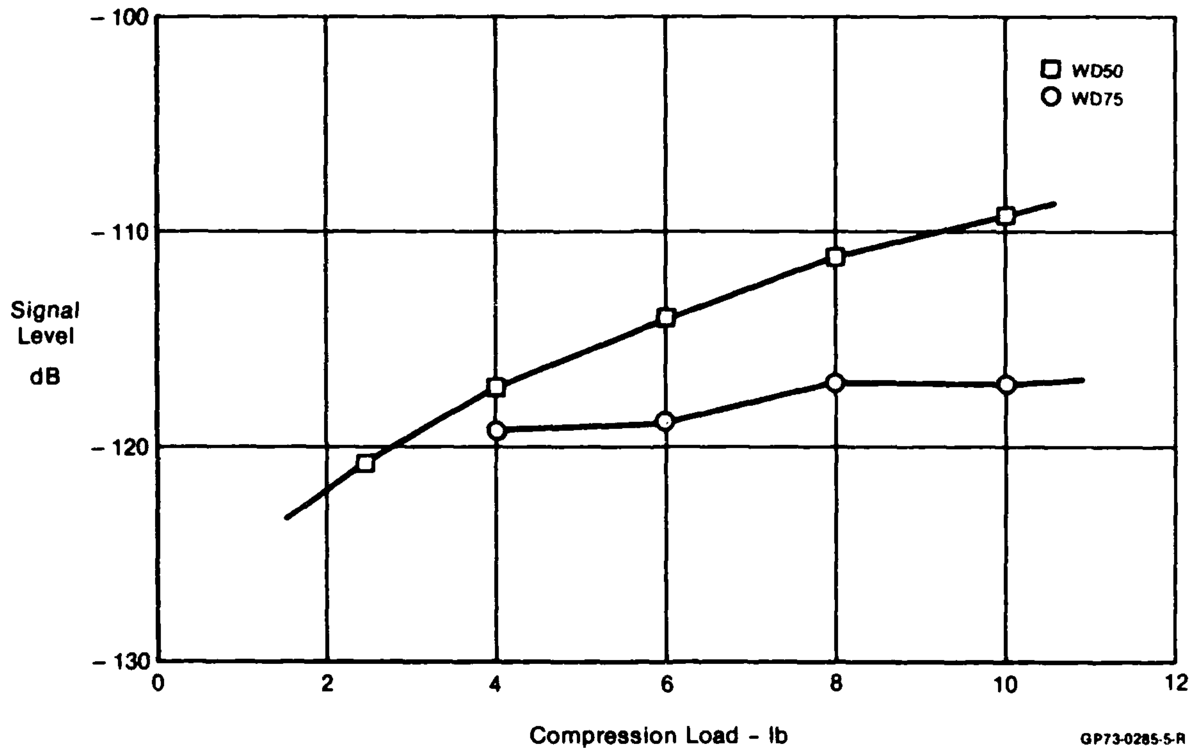


Figure 9. Air Coupled Search Unit Attenuation

transverse reciprocating motion by the drive belt. This scanning motion is shown schematically in Figure 10. This action provides for the full coverage of the part surface, but also introduces some difficult problems.

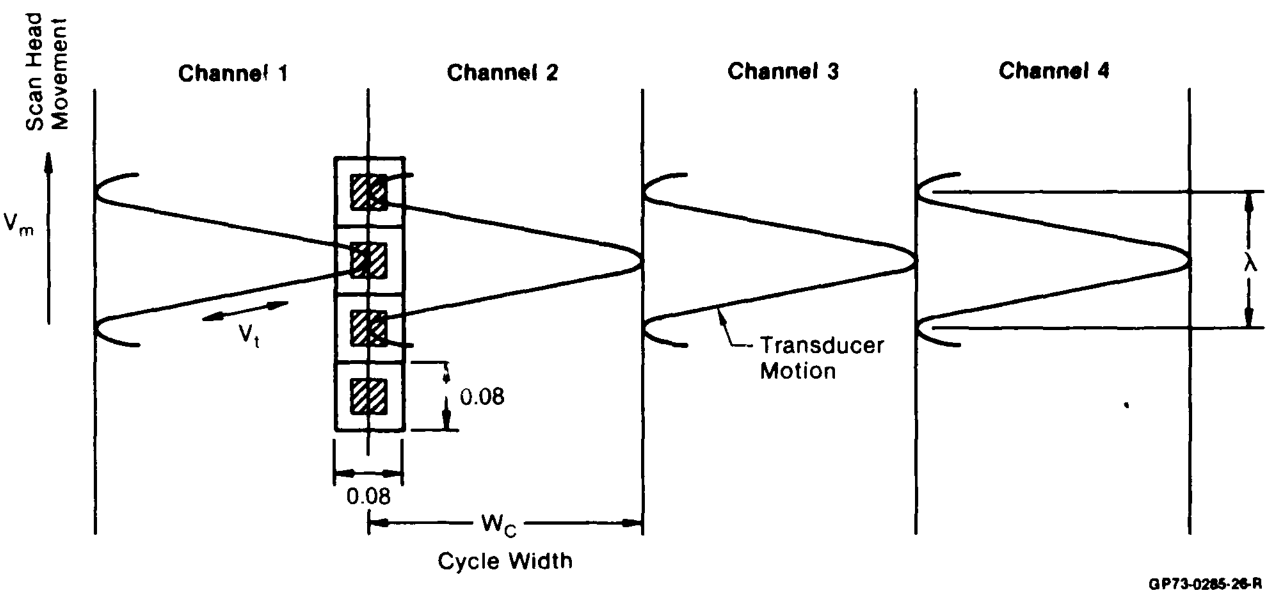


Figure 10. MAUS Scanning Motion

The MAUS was originally tested on composite parts using only a single channel of ultrasonic data. The software was modified to accept and process the data from four separate ultrasonic transducers. The proper timing and handling of the four channels is essential to the production of a coherent image from the multiple transducers. Early scanning with the MAUS using all four channels showed very good balance between the four channels and nearly transparent borders between adjacent channels when evaluated on flat components. However, the belt which held the four transducers appeared to be too stiff, and on curved specimens there was a tendency for the transducers to lift off of the part and lose ultrasonic coupling. This resulted in the appearance of dark "seams" between the adjacent channels. The cause for the drive belt stiffness was suspected to be related to a cable stiffness problem. These cables were replaced and rerouted to increase the bend radii in the cables, thereby increasing the flexibility. These steps appear to have eliminated the transducer lift-off problem and subsequent scans on the curved fuselage simulation panel looked good.

Another potential problem is that a transducer tip may snag on a protruding fastener or some other detail of the part surface. The initial design of the MAUS scanner addressed this hazard by placing large radiussed buttons on the nose of the transducer tips. The buttons were intended to lift the transducer tip over the surface irregularity with a minimum amount of "no scan" area. Another potential problem is that the high relative velocity between the probe tips and the part surface may result in a high sliding friction which produces a moment on the transducer drive belt. This friction is a function of the drive speed, the surface curvature and texture, the condition of the transducer tip, couplant quality, and the normal force applied to the transducer. The number of factors which affect the sliding friction made it difficult to predict and an area of considerable concern.

One approach to these problems was to provide a buffering interface between the probe tips and the part surface. We ordered and received a sample of 0.010 inch thick polyurethane film type MP1880 from JP Stevens & Co., Inc. This particular material is quite pliable and abrasion resistance and we evaluated it for use as an interface material between the transducer tips and the part surface. Initial evaluations of the polyurethane film showed that the ultrasonic velocity of the material was approximately 0.5×10^5 in/sec. This is fairly close to the published velocity of 0.7×10^5 in/sec. The fact that our measurement was made on a fairly thin sample may also contribute to some error in our velocity estimate. In any case, the velocity was sufficiently close to provide good acoustic coupling with a composite laminate. The two way transmission loss through the polyurethane film in a static test was less than 0.5 dB as measured in the back surface echo amplitude of a carbon epoxy specimen with and without the interface layer.

The preliminary evaluations of the polyurethane film were made by merely placing the sheet of material on the couplant wetting surface of the part and performing the tests. The only detrimental effect which was noted was the presence of a few air bubbles between the polyurethane sheet and the test specimen. These bubbles appeared in the test scans as voids. We expected that a slow, continuous flow of water between the film and the transducer tips might go a long ways toward eliminating or reducing the occurrence of these bubbles by providing a more uniform couplant layer.

A section of the material was attached to the front of the MAUS such that it could be draped underneath the front edge of the scan head and ride between the transducer tips and the part surface. A water distribution system was added to allow a small amount of water to flow down both the inside and the outside of the polyurethane sheet. Scan results using this approach were very encouraging. The layer of polyurethane wet well and remained fairly bubble free, particularly in the area of the transducers. It did, however add a small amount of resistance to the scan motion compared with the bare scanning of our reference specimens.

2.2.2.2 Scanning Speed - Preliminary evaluations of the scanning speed were made with the MAUS. The motor which drives the transducer belt in a reciprocating motion was producing 6.4 cycles per second. Referring back to Figure 10, we can see that with a cycle width of Wc and a manually driven forward velocity Vm, the transducer tips trace out a sinusoidal path. We want to control the wavelength of the sinusoidal path to be sure that the data is collected for the full part surface. Data is collected by the MAUS data processing system using a 0.04 by 0.04 inch pixel size. The data system can supply alternate lines of data using an averaging routine. This makes the pixel size effectively 0.04 by 0.08. A single cycle of the transducer provides two passes across the cycle width, Wc.

Since the sound beam diameter of the search units being used is substantially greater than 0.08 inch and the cycle travel length λ is small compared to the nominal cycle width (Wc) of 2 inches, we can approximate these two passes as parallel lines separated by half of the wavelength. With this approximation, the maximum wavelength for full coverage is 2 x 0.08 or 0.16 inch. Multiplying this wavelength by the motor driven cycle rate of 6.4 cycles per second gives a maximum forward velocity of 1.0 inch per second. At this velocity, we could cover an axial distance of 60 inches per minute. Since we have a total of four channels covering an 8 inch scan path, this yields a coverage of 8 x 60 / 144 or 3.33 ft^2 per minute or 100 ft^2 in 30 minutes. It is doubtful that we could operate at maximum speed all the time, but it would seem reasonable to expect to be able to achieve half the maximum in many cases and this would still achieve the required 100 ft^2 per hour.

As a result of the preliminary scan speed evaluations the MAUS software was modified to incorporate a velocity dependent data pixel size. This feature allows the MAUS to provide a high resolution scan at slow scan speeds and still provide full screen coverage at much higher scan speeds. In the original MAUS configuration, a discrete data point was required for each 0.04 by 0.04 inch area of the surface. If the scan head was moved too fast, the oscillating motion of the transducers could not keep up and a row of data points would be missed. This shows up on the C-scan as a white streak. Since the required flaw size is much larger than the 0.04 by 0.04 data point size, this causes the scan rate to be unnecessarily slow. With new software, the data sample can be recorded as up to 0.16 inch wide, depending on the actual scan speed. This allows the scanner to be moved up to four times as fast to cover larger areas. The increased data pixel size causes some spatial distortion of the outline of any flaws or geometric features, but a higher resolution display of these areas can be achieved simply by slowing down the forward motion of the scan head, or by back-tracking over the feature at a slower speed.

The dynamic index is achieved by having the data system paint the screen with four lines of data for each line of data read. The data is duplicated from the actual location to the next three points in front of it. If the scan head moves only 0.04 inch before the transducers pass that location again, then only one of the four lines is left behind and the other three lines plus a new line are repainted with the new data. If the scan head is moved more rapidly, up to four lines of data can be left behind without producing any white streaks.

The F/A-18 Inner Wing Skin was scanned to evaluate the ease of use and effectiveness of the MAUS on a large structure. The system clearly detected and displayed the intentionally included flaws although the thicker areas required slightly different settings than the thinner areas. Portions of the scanning operation and the data collected were recorded on video tape. A sample scan strip was timed to estimate the practical scan rate on full size structure. In this test, a five foot long strip was scanned in 90 seconds, yielding a scan speed of over 130 square feet per hour. While this was a straight line scan and included no changes in direction, the results were encouraging.

These scans were made with essentially no set-up time required for the MAUS. The gain and filter settings were set based on typical settings for laminates of the proper thickness range. The surface was prepared by squirting a thin layer off slightly soapy water over the area to be inspected. No other set-up was required to produce the inspection results.

2.2.3 Ultrasonic Transducer Development

2.2.3.1 Ultrasonic Spectral Attenuation - The optimal transducer characteristics depend heavily on the ability of the material to support the propagation of waves of various frequencies. We compared the frequency response of the back echo from carbon epoxy laminates of various thicknesses to the back response from a 0.25 inch thick glass plate using the same transducer. The carbon epoxy laminates used for this test were the 0.26 and 1.74 inch thick sections of the bulkhead beam, the 0.5 inch thick step of a step wedge and a 0.95 inch thick laminate from which the step wedge was cut. Two wide band transducers were used. One was a 2.25 MHz, 0.5 inch diameter, and one a 5.0 MHz, 0.375 diameter search unit. A Hewlett-Packard Spectrum Analyzer was used to measure the spectral response of the different back echoes. Care was taken to provide proper impedance matching between the amplifier and the spectrum analyzer and to avoid any problems with distortion due to amplifier saturation.

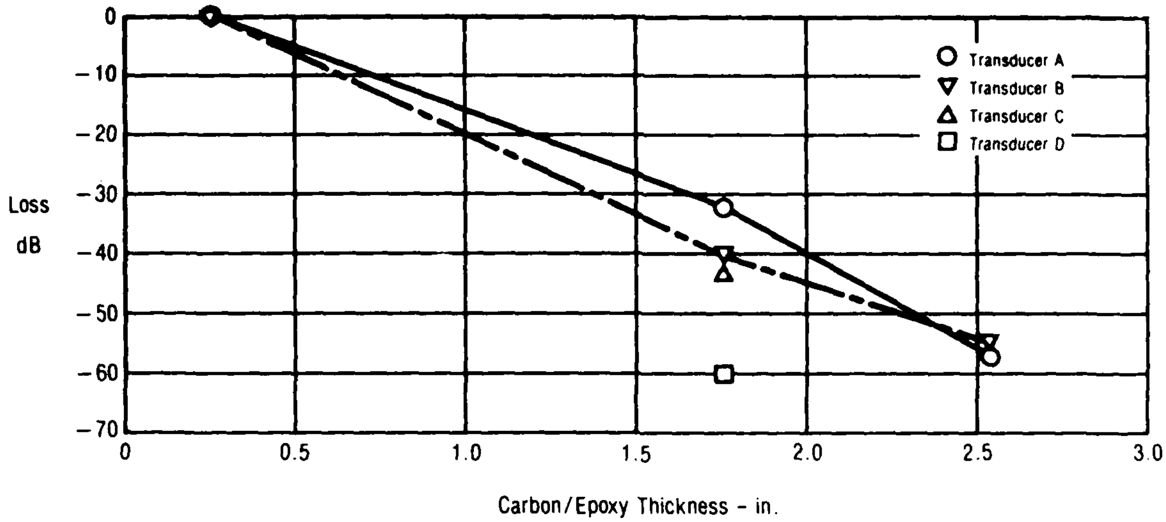
Several sets of data were collected by photographing the CRT output of the spectrum analyzer. The response amplitude at a given frequency was compared to the response amplitude of the same transducer at the same frequency from the glass plate. The data for each frequency and thickness were averaged and compared. The range of deviation from the average was +2.9 dB to -3.1 dB and the standard deviation for all the data was 1.2 dB.

These data indicate the increase in attenuation as a function of the interrogation frequency and as a function of material thickness and show quite high attenuation of frequencies over 5 MHz in laminates 1 inch or greater in thickness. The data was useful in determining the required characteristics of the ultrasonic transducers and associated electronics.

2.2.3.2 Thick Laminate Spectral Attenuation Evaluations - Current production composite laminates at MCAIR range in thickness from about 0.025 to about 1.0 inch thick. The specification of a working material thickness of 2.0 inches is therefore somewhat beyond our normal working experience. The larger thickness will generally limit the maximum usable frequency and will also impact the required system sensitivity and sound beam geometry. We have investigated several of the potential impacts associated with the inspection of 2.0 inch thick laminates.

The 0.25, 1.74, and 2.58 inch thick sections of the composite bulkhead beam were used to investigate a number of facets of thick laminate inspection. A series of transducers, all nominally 5.0 MHz, were used to determine the attenuation properties of the thick laminate. Though the transducers were all of the same nominal frequency, the performance characteristics varied widely. The sensitivity readings from each transducer was normalized by using the amplitude of the back surface echo from the 0.25 inch thick section as a reference for calculating dB loss through the other laminate thicknesses. These results are shown in Figure 11. These results show significant scatter, even at the 1.74 inch thickness.

In conjunction with these tests, a spectrum analyzer was used to investigate the effects of minor frequency spectrum differences on the performance of the different transducers. Figure 12 shows a sketch of the spectral response of the 'C' transducer from the front surface of the



Transducer

A 1/2 in., 5.0 MHz Panametrics A109S

B 1/4 in., 5.0 MHz K.B. Aerotech DFR

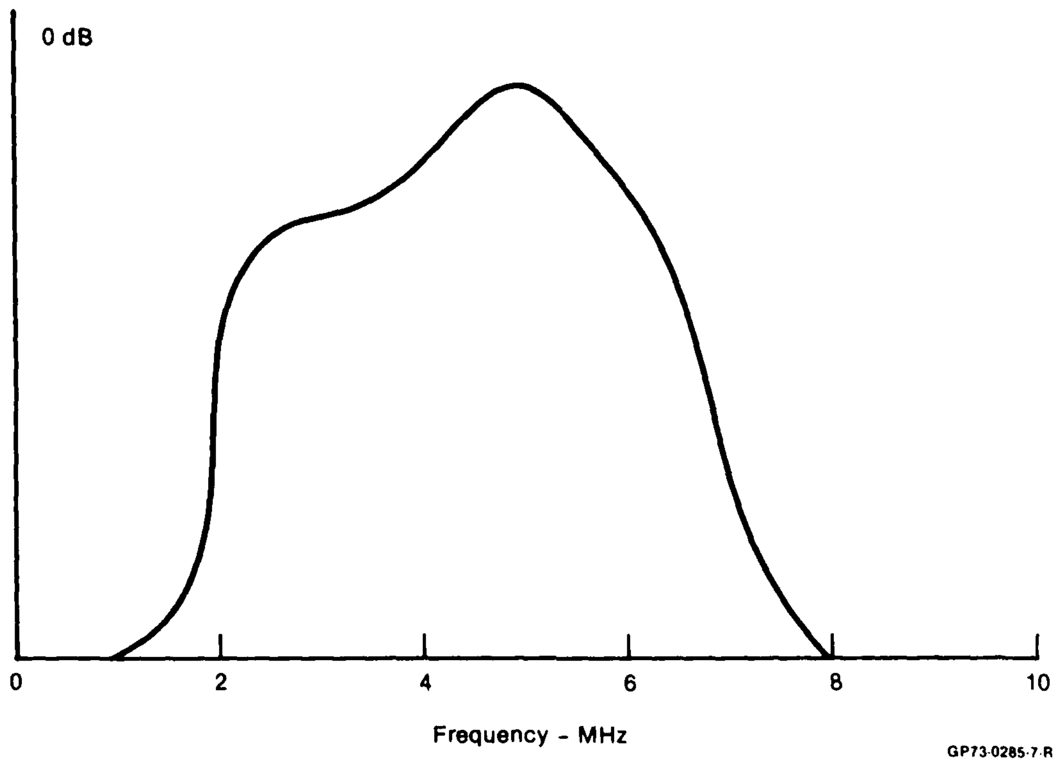
C 1/2 in., 5.0 MHz Nortec A-Z-1/2-5

D 1/2 in., 5.0 MHz K.B. Aerotech Alpha

C&D Are Immersion Units

GP73-0285-6-R

Figure 11. Attenuation Rates of 5 MHz Signals in C/E



GP73-0285-7-R

Figure 12. Front Surface Reflection Spectrum - Transducer "C"

bulkhead beam panel. Figure 13 shows the spectral content of the back surface echo in the 1.74 inch thick area from the 'C' transducer. The spectrum from the back surface echo shows essentially no energy content above 2.5 MHz. Since nearly all of the energy for this transducer is distributed in the 2 to 7 MHz range, it is clear that the laminate is significantly filtering the waveform.

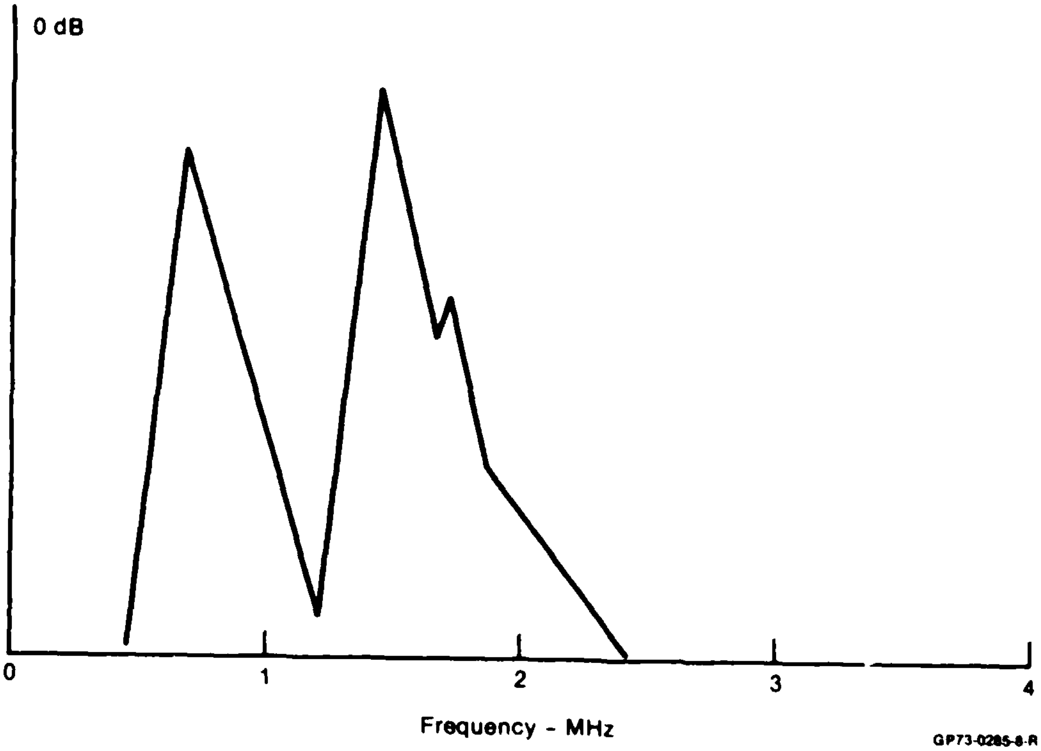


Figure 13. Back Surface Reflection Spectrum - Transducer "C"

Figure 14 shows the spectral content of the front surface echo for transducer 'D'. This spectrum shows substantially less energy in the 2-3 MHz band than the transducer 'C' profile seen in Figure 12. The total sensitivity of these two transducers differed by less than 1 dB in the 0.25 inch section. However, the attenuation curves in Figure 11 show a difference of about 17 dB between the two transducers at 1.74 inch.

It is clear that the total spectral content of a transducer will be much more important in the inspection of very thick laminates than it is for laminates of more moderate thickness. The upper frequency band edge will be important in determining the front surface resolution characteristics, and the lower band edge will determine the depth sensitivity. From these data it appears that thick laminate inspections should use ultrasonic search units with a fairly broad banded frequency spectrum and substantial energy

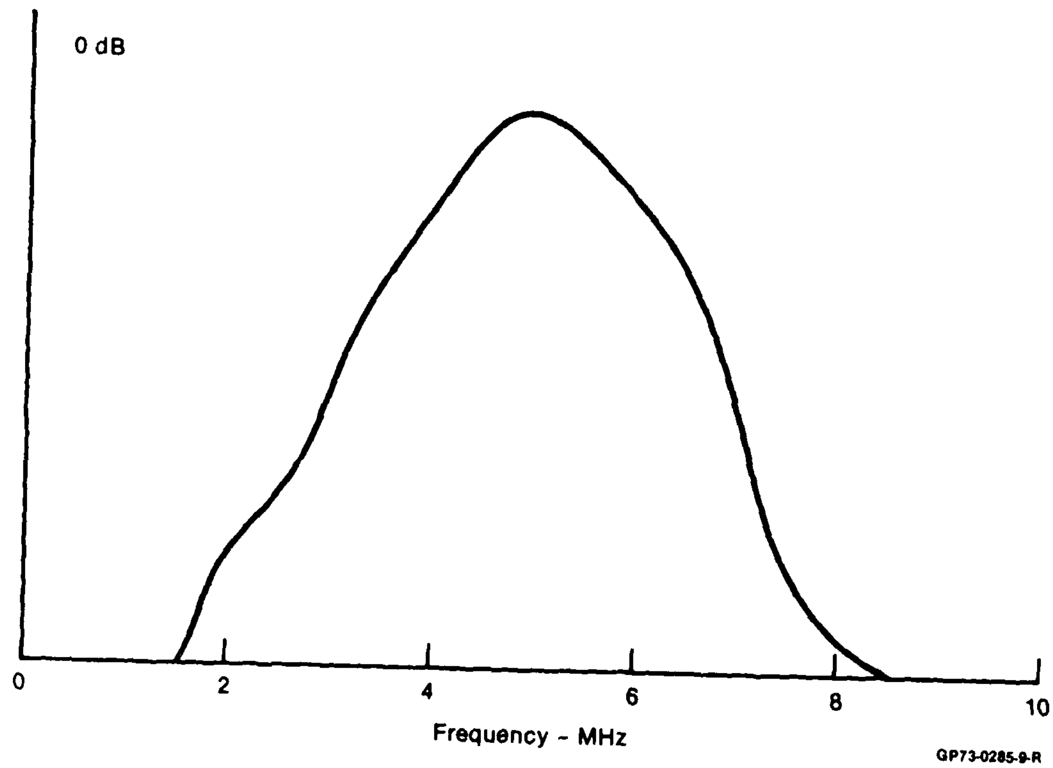


Figure 14. Front Surface Reflection Spectrum - Transducer "D"

available below 2.5 MHz. This spectral content must be achieved while maintaining a close impedance match to the pulser/receiver.

The range of attenuation for the composite parts to be inspected during this program was about 40 to 50 dB. The loop gain of a 5 MHz transducer is typically about -50 dB. With a pulser drive voltage of about 350 volts peak-to-peak, the range of analog signals would be about 1 volt to about 3.5 millivolts. With signals at this level, we had to closely specify the sensitivity of the ultrasonic transducer in addition to its frequency content.

2.2.3.3 Transducer Development - Early evaluations of the contact delay line transducers in the MAUS showed that they did not have the sensitivity needed for thick laminates. Consideration was given to the use of immersion transducers to provide additional penetration and avoid the delay line multiple echo which occurs in laminates greater than 1 inch thick. Other transducer technologies available included contact transducers, zero interface reflection transducers, and modified immersion transducers. Contact transducers, though very powerful, were ruled out due to near surface resolution and wear problems.

The zero interface probe solves the near surface problem by using a delay line material which is matched very closely to composites such that the front surface echo is very small. This allows very good near surface resolution using a lower frequency which provides greater penetration into the part. Initial evaluations of this approach in a static test showed an ability to obtain an easily readable second back echo from the 1.74 inch thick section of the bulkhead beam specimen. The same probe was able to clearly detect a hole 0.050 inch from the back surface of the 1.74 inch section and a hole 0.020 inch from the front surface of the 0.25 inch section. These search units, though, use a soft wear face material to provide an impedance matching layer which is not variable in a MAUS scanning operation.

The third approach was to use an immersion type transducer specified to possess the properties necessary to allow inspection of carbon epoxy laminates two inches thick with the desired resolution capabilities. We received two prototype 5 MHz immersion search units fabricated by KB Aerotech to our specification. One was 0.375 inch diameter and the other was 0.500 inch diameter. The sensitivity of these transducers were compared to several available 5 MHz high power search units.

The results of these evaluations are summarized in Table 3. While the loop insertion loss for these transducers show generally less sensitivity as measured by the amplitude of echoes from the front surface of steel and carbon epoxy, the frequency analysis shows a higher relative content of low frequency energy. This increase results from a modification to the transducer element backing material.

TABLE 3. TRANSDUCER SENSITIVITY SUMMARY

Transducer Description[1]	Gain - Steel (dB)	Gain - C/E (dB)	Relative Spectral Level Off Steel (dB)				
			1.5 MHz	2.0 MHz	3.0 MHz	4.0 MHz	5.0 MHz
1 0.375 in. Dia. 3.5 in. Focus, Prototype	−50.0	−55.1	−25	−15	−3	0	−3
2 0.375 in. Dia. 3.0 in. Focus, Stock	−40.9	−45.5	−25	−18	−5	0	−1
3 0.500 in. Dia. 4.0 in. Focus, Prototype	−50.0	−45.5	−12	−8	−3	−1	0
4 0.500 in. Dia. 4.0 in. Focus, Stock	49.2	53.4	17	12	5	2	0
5 0.500 in. Dia. 1.5 in. Focus, Stock	−43.5	54.9	−14	−12	−6	−1	−1
6 0.500 in. Dia. 1.0 in. Focus, Stock	−45.3	−51.8	No Spectral Data				

(1) All transducers are KB Aerotech. 5 MHz nominal frequency. All stock transducers are alpha type light damping. Prototypes have special damping.

GP73-0285-25-R

Transducers 1, 3, and 6 were selected to evaluate the penetration characteristics in the thick carbon epoxy bulkhead beam. The signal strength from the front and back surface of the beam were compared. For these tests the search units were operated in the system having a nominal input impedance of 50 ohms. They were excited by a -120 volt spike with a fall time of 10-15 nanoseconds, to provide a broadband input. The results of these tests are summarized below and show a very persistent signal for the 0.5 inch prototype (#3).

TRANSDUCER	LOSS dB
#1	-44
#3	-36
#6	-60

Finally, the 0.5 inch diameter prototype, #3, was used to make an immersion scan of the thick carbon epoxy bulkhead beam. The search unit was able to resolve all of the flat bottomed hole reflectors in the 1.74 inch thick section of this beam. Those holes are located at depths of 0.050, 0.250, and 1.00, and 1.50 inches.

Although transducer #3 had a misaligned beam, it performed well for our applications. The problem with beam alignment can be corrected in production units. Two units similar to #3 were ordered for further evaluation in the thick part scanner concept demonstration.

The test data from KB Aerotech on these transducers indicate that they had an electrical impedance of 50 ohms, a loop insertion loss of -44.4 dB for S/N L27519 and -44.1 dB for S/N L27520. This is about 4 dB better than the prototype (#3). The spectral photographs indicate that the content at 1.5 and 2.0 MHz are about 2 dB below the prototype.

We fabricated a sheet metal concept demonstrator for the inspection of thick laminates. The two transducers were mounted in the fixture which supported them about 1.3 inches above the part. A piece of Stevens MP1880 polyurethane material 0.01 inch thick was wrapped around the bottom of the fixture such that a contact area about 1 inch wide is provided. The bag was filled with a fluid to couple the sound beam to the surface of the part. This provides a test environment for the transducers which is representative of the environment in which we propose to use them.

This concept was evaluated on several laminates using water as a couplant between the bag and the inspection surface. The bag was filled with 10W-30 motor oil. This configuration provided a consistent coupling of the sound into the part, though the front surface echo amplitude was somewhat lower than expected. The loop insertion loss for each transducer in the configuration was about -67 dB and the peak spectral amplitude was at about 3 MHz. The back echo amplitude from the 1.74 inch thick laminate was about 88 dB below the initial excitation voltage. This is about a 2 to 3 dB improvement over the initial prototype transducers.

Flaw resolution was evaluated using the flat bottomed holes in the 1.74 inch thick section of the bulkhead specimen and using some mylar inserts in material about 0.35 inches thick. These tests showed excellent correlation of indicated flaw depth with flaw depth determined using ultrasonic thickness gaging techniques for flaws ranging in depth from 0.028 to 1.68 inch below the front surface.

Following these tests, the oil was removed from the polyurethane bag and it was filled with water. With this configuration, the loop insertion loss improved to -59 dB and the signal from the back surface of the 1.74 inch thick laminate improved by 5 dB. Also the radio frequency spectrum increased by about 4 dB at 4 MHz and by more than 10 dB at higher frequencies.

In another series of tests, we filled the bag with ethylene glycol (antifreeze). This material showed very good transmission properties. The transducers were driven by a Panametrics 5052 pulser-receiver and the signals were evaluated by a MCAIR Ultrasonic Signal Processer. This provides an electronic environment very similar to the MAUS and should provide representative indications of the performance capabilities of these transducers in MAUS applications. This configuration was evaluated using the 1.74 inch thick section of the thick composite bulkhead beam, and a 0.25 inch thick laminate which containing mylar inserts at various depths. The front and back surface loop insertion loss of each transducer was measured on the 1.74 inch thick laminate. Once again the transducers gave essentially identical results of -59 dB for the front surface and -83 dB for the back surface. The flat bottomed holes in the 1.74 in thick laminate were used to evaluate the far surface resolution. The hole 0.05 inch from the back surface was easily resolved. Near surface resolution was evaluated on the 0.25 in thick laminate using the mylar inserts. Inserts at depths of 0.01, 0.025 and 0.05 in were easily resolved. In none of these tests has the presence of the polyurethane bag at the interface to the front surface of the part been distinguishable from the front surface interface. This concept of using immersion transducers in a captive fluid appears feasible for the inspections of a wide variety of laminates. Some conceptual designs of a "bag" scanner were layed out. Potential problems with the designs were:

1. Filling and eliminating air in the bag.
2. Bag strength and resistance to puncture and wear.
3. Mechanical coupling to the transducer without fluid leakage.
4. Electrical transducer connections without fluid leakage.
5. How to hold transducers normal to part surface.

The advantages of the "bag" scanner compared to the belt and delay line approach were:

1. Two inch thick composite laminate inspection capability.
2. Low relative scan velocity at part surface (motion only in index direction).

The advantages of the belt and delay line approach compared to the bag scanner were:

1. Compound curve following; 36 inch radius across scan direction, 5 inch radius in index direction.
2. Simpler mechanical design.
3. Ease of changing transducers.
4. Standard, off the shelf transducers.

For these reasons and our familiarity with the concept using the MAUS Prototype, the belt and delay line approach was pursued in the Task III. We felt the "bag" scanner concept had significant potential and should be explored in future work.

2.2.3.4 Array Transducer Evaluations - The high relative velocity between the transducer tips and the part surface provides particular challenges to the coupling technique. One possible alternative to the reciprocating transducer concept that was looked at was to use an array transducer and perform the scanning electronically. An 8 element array transducer was ordered on consignment from KB Aerotech to evaluate this approach. The array transducer was a highly damped 5 MHz unit with 0.125 x 0.400 inch elements and was housed in an immersion case. The elements were configured as shown in Figure 15, with the 0.400 inch sides being adjacent so as to produce an array that is 0.400 inch wide by 8 elements long. The elements are identified as "A" through "H".

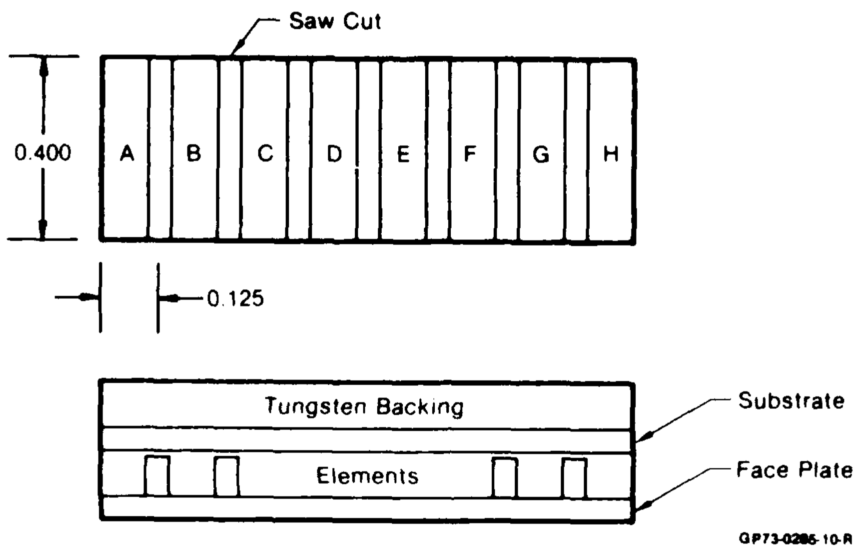


Figure 15. Array Transducer Configuration

In the initial evaluations of this search unit, we have characterized the individual elements for uniformity and system compatibility. In the first test, we measured the AC impedance of elements A,B,C, and F. The impedance values with the search unit in water were measured with a Hewlett-Packard 4815A Vector Impedance Meter. The impedance ranged from 70 ohms with a phase angle of -82° at 2.0 MHz to 8.4 ohms with a 17° phase angle at 6.0 MHz. The 5.0 MHz impedance was 23 ohms with a phase angle of -48°. The frequency which produced a 0° phase angle was 7.2 MHz and the resistance at this frequency was 7.4 ohms. With the search unit in air, the 5.0 MHz impedance was 25 ohms with a phase angle of -71°. The impedance of each of the elements measured was within 1 ohm and 2° of each of the others.

Loop gain measurements were made of the same elements used in the impedance tests. The loop gain was greatest when the element was contacting the surface of the reflector and remained constant out to about 0.06 inch. Measurements were taken out to a water path of about 1.5 inches. The loop gain of element A from a stainless steel plate reflector was -46 dB at contact, dropping to -49 dB at 1.5 inches. The loop gain in contact with a carbon epoxy laminate was -51 dB at the entry surface and -87 dB using the back echo from a 0.95 inch thick laminate. Interestingly, there was a nearly linear drop of 3 dB in loop gain going from element A to F.

Crosstalk was evaluated between the elements of the search unit. We found that with the initial pulse signal in element A at 116 volts, a signal of 7 millivolts was generated in element B and 3.5 millivolts in element H. We do not feel that these very small signals will provide any interference in a multiplexed application.

Though a stringent depth resolution test was not run, an echo train from a 0.26 inch thick laminate with an inclusion approximately 0.030 inch below the surface showed clean resolution of the inclusion, as shown in Figure 16. While the baseline showed only a slight break between the front surface echo and the inclusion echo, the pulse echo flaw detection logic would permit the detection of flaws somewhat closer to the surface than this. Some improvement in resolution could be achieved by making the element from lead metaniobate rather than the lead zirconate titanate that was used for the search unit we evaluated, but this would probably result in a reduction in the ability of the transducer to inspect thick laminates. The evaluated transducer was already somewhat below the gain level required to inspect carbon epoxy laminates 2 inches thick. Although the array evaluated showed promise, its application to a MAUS large area scanner presents several development problems. Major concerns were cabling, size of electronic package, and mechanical flexibility (conform to a part surface). We felt that array technology is applicable to a smaller MAUS scanner for the inspection of complex surfaces such as "T" and "J" sections.

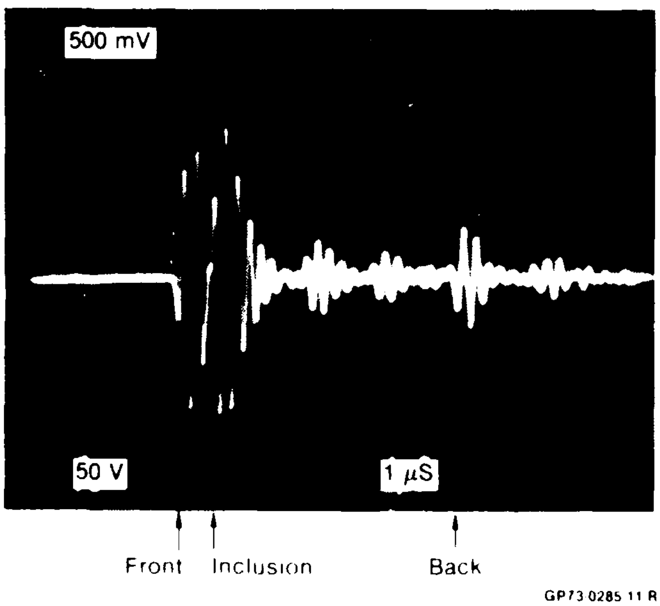


Figure 16. Ultrasonic signal Pattern From an 0.26 in. Thick Carbon/Epoxy Laminate Using the Array Transducer

2.2.4 MAUS Scanning Evaluations

2.2.4.1 Thick Laminate Scans - A carbon epoxy reference panel approximately 7 x 11 in. and 0.95 in. thick was modified by drilling 16 0.25 in. diameter flat bottomed holes to various depths, as shown in Figure 17. Hole depths range from 0.04 in. to 0.10 in. and from 0.80 in. to 0.87 in. These holes provide a measure of the front and back surface resolution capabilities of the MAUS scanner with laminates up to approximately 1 inch thick. The MAUS was fitted with four KB Aerotech thickness gaging transducers which are 5 MHz 0.25 in. diameter high resolution transducers with 0.75 in. long polystyrene delay tips. The delay tips provide approximately 15 to 16 microseconds of delay, during which data from the part can be taken before the first multiple of the front surface echo interferes with the signal pattern. This time window is sufficient to allow the inspection of a carbon epoxy laminate approximately 0.90 to 0.95 in. thick.

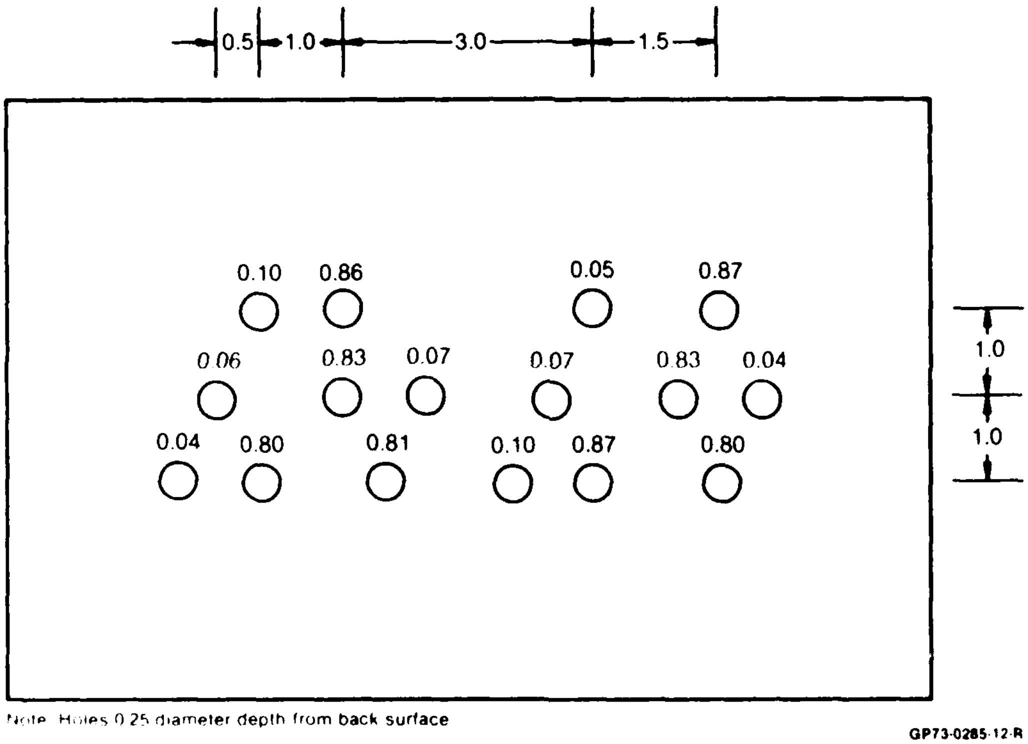
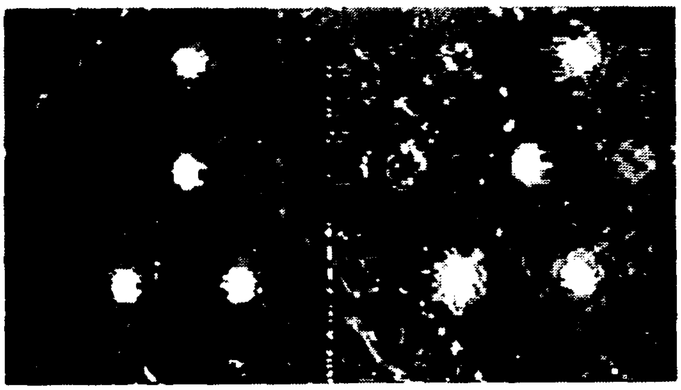


Figure 17. Flat Bottomed Hole Pattern in 0.95 In. Thick Carbon/Epoxy Laminate

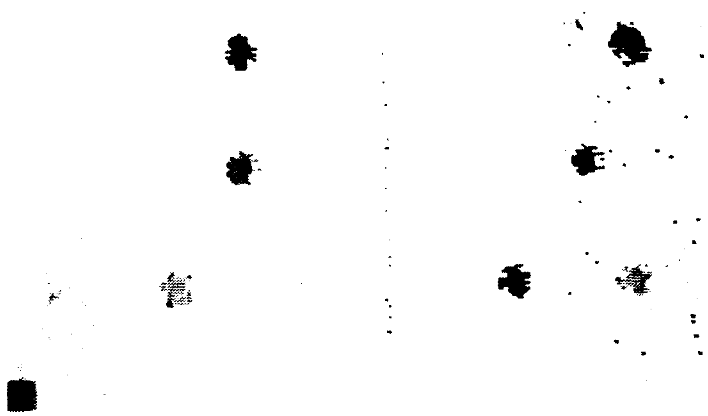
Our first delay lines were made of polystyrene, which is a standard delay line material. As noted they were 3/4 inch long and 1/4 inch in diameter. Threads were machined into the walls for attachment to the MAUS belt drive. This threading operation apparently stressed the polystyrene, as the delays became cracked after less than 1/2 hour of use. Different thread cuts were tried to relieve the stress to no avail. Finally a "crosslinked" polystyrene was tried. This material is much stronger and gave less than a 1 dB difference in ultrasonic signal strength at the 5 MHz search frequency. The four cross linked polystyrene delay lines are still in the MAUS prototype, having been in use since October 1985. They show wear from surface abrasion, but are still very fuctional.

A scan of the 0.95 in. thick panel using the cross linked delay lines is shown in Figure 18 and indicates that all 16 of the flat bottomed holes were detectable, although the deepest holes (0.04 and 0.05 from the back surface) are a bit difficult to distinguish from the noise. In some scans of this part, those holes were clearly visible, while in others, only a slight shading was detectable. In each case, the scan images were generated as the specimen was scanned, and the graphics window could then be adjusted to show all of the flaws, or to highlight just the near surface or the far surface flaws. The prototype MAUS used to make these scans has a 16 gray level graphics system. This places some limitations on near and far surface resolution capability. The breadboard system utilizes a 64 gray level graphics system. This helps compensate for the limited gray shades. Figure 19 shows the results with the scan window adjusted to show just the near surface flaws. With the window so adjusted, the 0.80 and 0.81 holes can easily be distinguished from the 0.83 holes, and the 0.86 and 0.87 holes can be easily distinguished from each of the other two groups. When the window is adjusted to highlight the back surface flaws, as shown in Figure 20, the 0.04, 0.06, and 0.10 holes clearly contrast with each other.



GP73-0285-13-R

Figure 18. MAUS Scan Showing All 16 Flat Bottomed Holes



GP73-0285-14-R

Figure 19. Window Mode Detail of Near Surface Holes

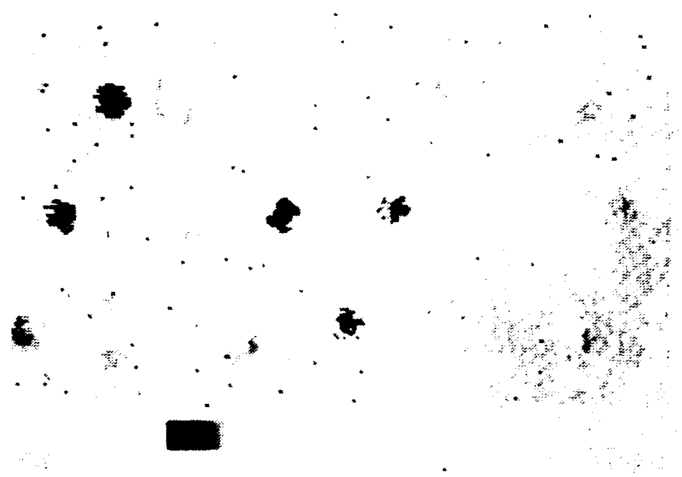


Figure 20. Window Mode Detail of Far Surface Holes

The above scans were able to demonstrate the ability of the MAUS to function well with laminates up to about 0.9 inch thick. The limitations of the delay lines, as well as the penetration capability of the current probes limit the ability to scan laminates over 1 inch thick. Several approaches to increasing the inspection range to at least 2.0 inches have been mentioned previously.

2.2.4.2 Hat Panel Scans - The MAUS was used to scan the curved hat stiffened panel, and it performed quite well. In fact, all thirteen of the built-in flaws, shown in Figure 3, were readily detected. The prototype MAUS could only display the ultrasonic results for a 4" x 8" area of the part surface at any one time. Several such areas of the curved hat stiffened panel are shown in the Figures 21 through 24. Both color and black-and-white graphics presentations are available; however, for clarity, only the black and white displays are shown here. The system can be switched from one display mode to another quite easily without rescanning the part. The basic skin thickness of the part is the dominant shade in each of the figures. The cocured hat stiffeners add thickness to the skin and are seen in the photographs as the wide horizontal bands. They show as a lighter gray shades in the figures.

Careful examination of the scans reveals the boundaries between each of the separate transducer channels. In fact, the second transducer from the right is slightly defective and produces a small black mark each time it crosses a skin to hat flange interface. The scans are filled top-to-bottom, or bottom-to-top as the MAUS is moved along the surface of the part. The circular or oval indications in each of the scans are produced by lead tape tabs placed on the surface of the specimen. These tabs aid in providing a close location reference between the scan and the part surface.

2.2.5 TAV-8B Forward Fuselage Panel Evaluation - The TAV-8B Forward Fuselage demonstration panel is a thin carbon epoxy laminate fabricated primarily from a woven carbon fabric material. The geometry of the part is very complex, consisting of extensive compound curvature, numerous integral, cocured hat stiffeners, and many areas of local ply build up. We used this panel to evaluate the ability of the system to detect and discriminate flaws at multiple depths in a thin laminate and to detect flaws in the substructure at or beyond the normal skin thickness. Because the woven material is also inherently noisier in ultrasonic examinations, this part also provided us with an opportunity to evaluate the ability of the MAUS to cope with noisy signal patterns.

2.2.5.1 Scanning Capability - The inspections of the Forward Fuselage panel were accomplished quite easily. In spite of the relatively thin skin thickness, complex geometry, and high surface curvature, the MAUS covered the inspection area quickly and easily. Tap water with a small amount of hand soap, used as a wetting agent, was squirted over an area to be scanned. This provided good coupling of the ultrasound and did not dry too fast. It was quite easy to provide adequate coupling for the largest area an inspector could scan while standing in one place. The nose barrel section of the TAV-8B fuselage panel curves at substantially tighter radius than the required 30 inches. In spite of this, very little problem was encountered with obtaining good ultrasonic data. In a few of the tightest areas, a corner of the scan head housing did drag on the part surface. This problem can be eliminated by a slight rework of the case side plates.

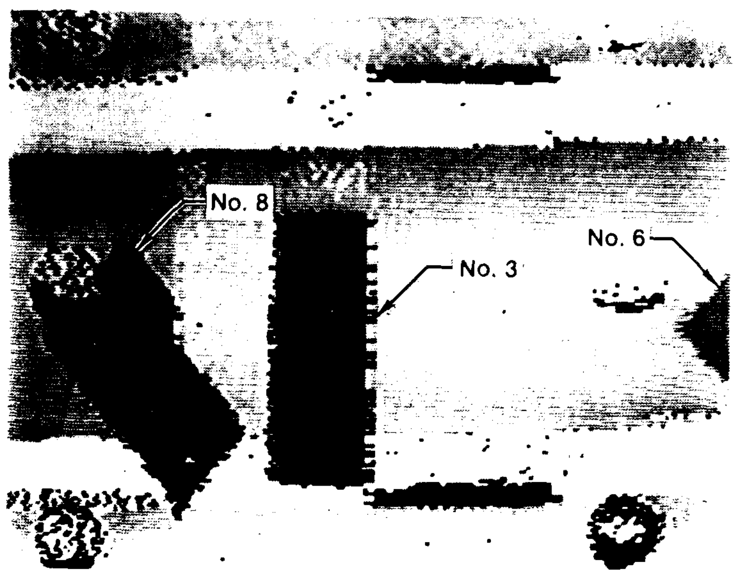


Figure 21. MAUS Scan of Hat Panel
Flaws 3, 6, and 8

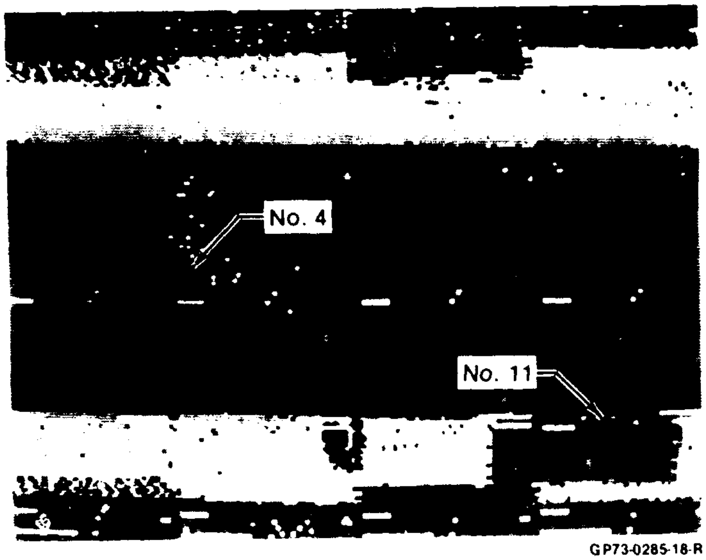


Figure 22. MAUS Scan of Hat Panel
Flaws 4 and 11

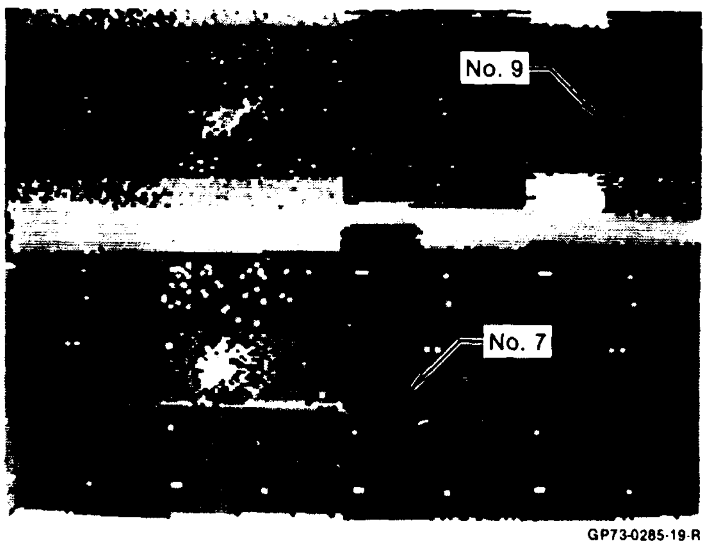
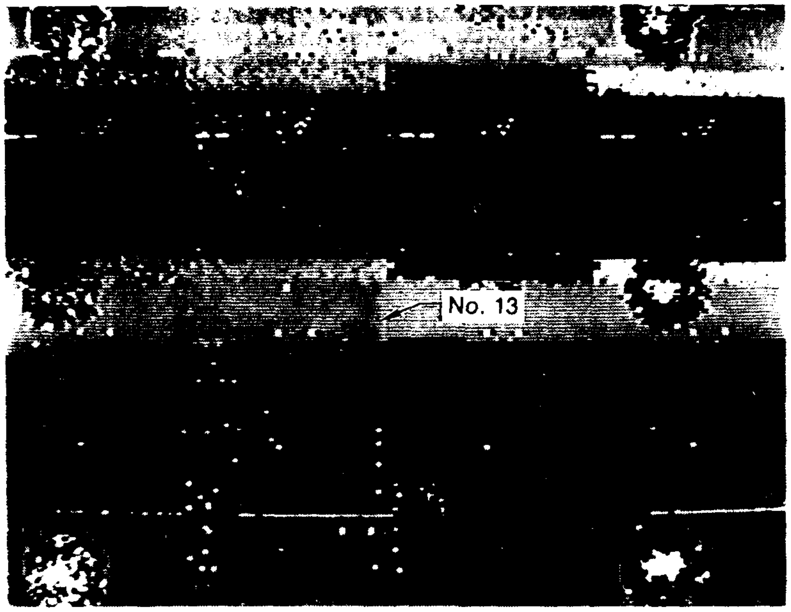


Figure 23. MAUS Scan of Hat Panel
Flaws 7 and 9



GP73-0285-20-R

Figure 24. MAUS Scan of Hat Panel
Flaw 13

2.2.5.2 Flaw Detection Capability - Of the 40 intentional flaws in the panel, 32 were readily detected by the MAUS. Of the remaining eight, five could be detected with some difficulty. Four of these five are in the flange plies of a hat stiffener (numbers 11, 19, 27, and 33) and the fifth (number 40) is in the skin plies directly over a hat stiffener. Two flaws, both of which are located in the flange plies of a hat stiffener (numbers 35 and 39), could not be detected, and one of the flaw inserts (number 25) had been mislocated in an rabbet area of the part where the geometry does not permit the MAUS to scan.

For those flaws which were difficult to detect or which we were not able to detect, the primary problem appears to be a difficulty in obtaining clear back surface resolution. While the ultrasonic signals used by the MAUS can generally resolve the flaw insert, it is in many cases difficult to reliably differentiate these minor thickness changes from other, acceptable and non-flaw related thickness changes. Another problem is that, due to hardware availability, the prototype MAUS on which these scans were made operates on a graphics system which uses only 16 shades of gray. This frequently produces a depth resolution of 0.040 inch. In some cases, the small change in indicated thickness caused by a far surface flaw is not enough to produce a gray level change. On the breadboard system we used a graphics system which provides 64 to 200 shades of gray. With this increased depth resolution, we expect that several of these flaws, particularly those for which detection was marginal, will be much easier to detect. Highly contrast colors can also be used on the breadboard system to distinguish surface flaws.

2.2.6 F/A-18 Inner Wing Panel Evaluations - The F/A-18 Inner Wing Skin Panel is fabricated from the more conventional unidirectional carbon epoxy broad-goods in a crossplied layup. The Wing Skin provides substantially thicker laminate sections and numerous tapered, ply drop-off regions. This provided an opportunity to evaluate the performance of the MAUS in thicker sections and in regions where the front and back surfaces were not parallel.

2.2.6.1 Inspection Procedure - The MAUS uses one of four thickness settings during scanning. Each thickness setting corresponds to a different combination of resolution and maximum thickness. At the highest resolution setting, data is recorded at a resolution which corresponds to 0.0012 inch of carbon epoxy. At that resolution, we can inspect up to about 0.31 inch of material. One might think that since the nominal ply thickness is 0.0052 inch, a resolution step of 0.0012 inch is of no value. However, the finer resolution step provides greater separation and less ambiguity for flaws that are near the back surface. The next thickness setting for the MAUS covers twice the material thickness at twice the resolution step and each subsequent setting doubles the maximum thickness of the previous.

The F/A-18 Inner Wing Skin panel has a maximum thickness of 0.84 inch, so the third thickness setting was used. This setting provides a maximum thickness of 1.2 inches at a resolution of 0.0048 inch. While this resolution is theoretically sufficient to uniquely identify the flaw depth to a ply level, any small error introduced into the system would cause an error in that estimation. Further, a flaw one resolution step from another interface, such as the back surface, frequently gets confused with that interface, particularly with the sixteen gray shade graphics system.

2.2.6.2 Flaw Detection Capability - With the 1.2 inch thickness setting, all but two of the inserts were detected, although three were difficult to see and correctly identify. The inserts which were not readily seen are identified below:

Condition	Flaw No.	Depth Below OML	Flaw Distance from Back Surface
Missed	6	0.333 Deep	0.021 from back surface
Missed	23	0.385 Deep	0.010 from back surface
Poor	29	0.811 Deep	0.026 from back surface
Poor	31	0.790 Deep	0.047 from back surface
Poor	27	0.520-0.645	0.067 from back surface

Note that both of the flaws that were missed are in areas of moderate depth, but are very close to the back surface. This indicates that, at this thickness setting, and with the 16 gray level graphics, the MAUS was not able to distinguish these flaws from the back surface. Flaws number 29 and 31 are also fairly close to the back surface and are deep in the panel as well. This contributed to the difficulty encountered in detecting them. Flaw number 27 is not particularly close to the back surface of the part, but is located in a tapered region of the part. This means that the surface of the flaw is not parallel to the surface of the part and the resulting flaw echo is weaker. This is probably the main reason that this flaw did not show up clearly.

There are only a few areas of the Inner Wing Skin which exceed 0.62 inch thickness, the maximum thickness for setting 2. We therefore rescanned the panel to determine the effects of using this higher resolution setting. At this setting, flaw number 23 was detected, as were numbers 29, 31, and 27; however, four other flaws were missed, located primarily in the thicker areas of the part. It is surprising that flaw number six was missed at this thickness setting. It was, however, detected at the highest resolution thickness setting, even though it should have been out of range.

2.2.6.3 Evaluation of Flaw Detection Problems - The phenomenon described above led us to closely analyze the procedure used by the MAUS to identify flaws and try to determine the source of some of these problems. One problem of particular interest was the detection of flaws beyond the theoretical limit of depth. In instances where this had been seen it was noticed that the indicated depth of the flaw was frequently far different from the actual known depth. This turned out to be the result of a phenomenon in which the counter continues to run, even beyond the theoretical maximum thickness of the part, and the computer folds this count over to where it appears to be at the front surface again.

This effect can be explained if one understands the method used by the MAUS to measure thickness. The MAUS measures flaw depth by measuring the period of time required for an ultrasonic pulse to travel from the front surface of the part to the flaw and back. Since the velocity of sound in carbon epoxy is relatively constant, this time is directly related to the depth of the flaw. The MAUS uses a 16 bit binary counter to measure the time delay. Every 20 nanoseconds, the counter value increases by one. A 16 bit counter can continue to count up to a decimal equivalent of over 65,000 before the counter is full. But, the MAUS can only process data that goes up to 256, or the equivalent of 8 bits. At the highest resolution setting, the MAUS reads the highest resolution eight bits of the counter, bits 1 through 8. At the next thickness setting, the MAUS reads counter bits 2 through 9. This provides a maximum thickness value exactly twice that of the highest resolution setting. At thickness setting 3, the MAUS reads bits 3 through 10 and at thickness setting 4, bits 4 through 11.

It now becomes a little clearer why the flaws below the maximum thickness setting were indicating near the front surface of the part. Since the counter continued to run, the lowest 8 bits reset and started to count again at zero, just as an automobile with 110,000 miles has an odometer reading of only 10,000. A software modification was provided in the breadboard system which caused the indicated thickness to remain at the maximum value, or else give a unique indication when the maximum thickness value is reached.

In cases where the counter problem did not explain the flaw detection problems, the A-scan waveform of the signals from the flaws were investigated. Attempts were made to optimize the instrument settings for each of the flaws by trying to see if there were some pattern that would develop that which would modify our approach to setting up the MAUS. These attempts were limited by our use of a single slope time corrected gain circuit. If the TCG was increased enough to get tapered flaws (such as #27) this produced too much gain and oversensitivity in the 0.2 to 0.4 inch range. The solution was to implement a potentiometer controlled delay in the TCG. A 2.5 microsecond (or .16 inches in C/E) worked best for flaws in the F/A-18 wing skin. This delay also cleaned up front surface indications. The TCG start signal was apparently generating a noise spike at turn on into the front surface RF signal. With a delay in TCG start, lower video filtering could be used with improved near surface resolution resulting.

2.3 TASK III - BREADBOARD SYSTEM DESIGN

The Large Area Scanner breadboard system was developed using technology from three existing systems (Figure 25); the MAUS Prototype unit, the MAUS Development Station, and an ADIS (Automated Data Inspection System). Each of these systems were used in particular phases of the development. All of these systems are similar and are based on Intel's Multibus I using an 8086 microprocessor.

The electronics for the MAUS Prototype was implemented early in this program and used extensively during Task II. Its purpose was to provide a simple test-bed for ultrasonic data system development and mechanical scanner software development. The size and weight of the electronics package was kept to a minimum to make it portable. This allowed the MAUS to be transported to remote areas and tested in a more realistic environment than normally found in a laboratory. The MAUS prototype has only the basic electronics, it contains no disk or tape for storage, and has no plotting capability. In fact, to minimize the card count, the unit has only a four bit imaging card (giving 16 shades of gray or colors). This limits the image resolution and the near and far surface resolution. Even though the electronics are simplistic, the device proved to be very effective in Task II evaluations.

Much of the imaging and data analysis software for the breadboard system was developed using the MAUS Development Station. The MAUS Development Station consists of a USP (Ultrasonic Signal Processor) chassis, an Intel 380 computer system, CRT monitor, oscilloscope, and other auxiliary cables and equipment needed for MAUS development. This hardware is mounted in a double bay, 6 ft. high electronics rack. Interface hardware and software has been developed to operate the mechanical scanner from the MAUS Development Station or an ADIS System.

ADIS is an ultrasonic data acquisition and imaging system developed and marketed by McDonnell Douglas. The particular unit used in this program is part of the laboratory facility dedicated to hardware and software development. Since the ADIS is equipped with a 35 byte Winchester disk, a floppy disk, and a plotter, it was an ideal environment to develop the data archival and data hard copy requirements of this program. The tape interface hardware and software was also developed on the ADIS.

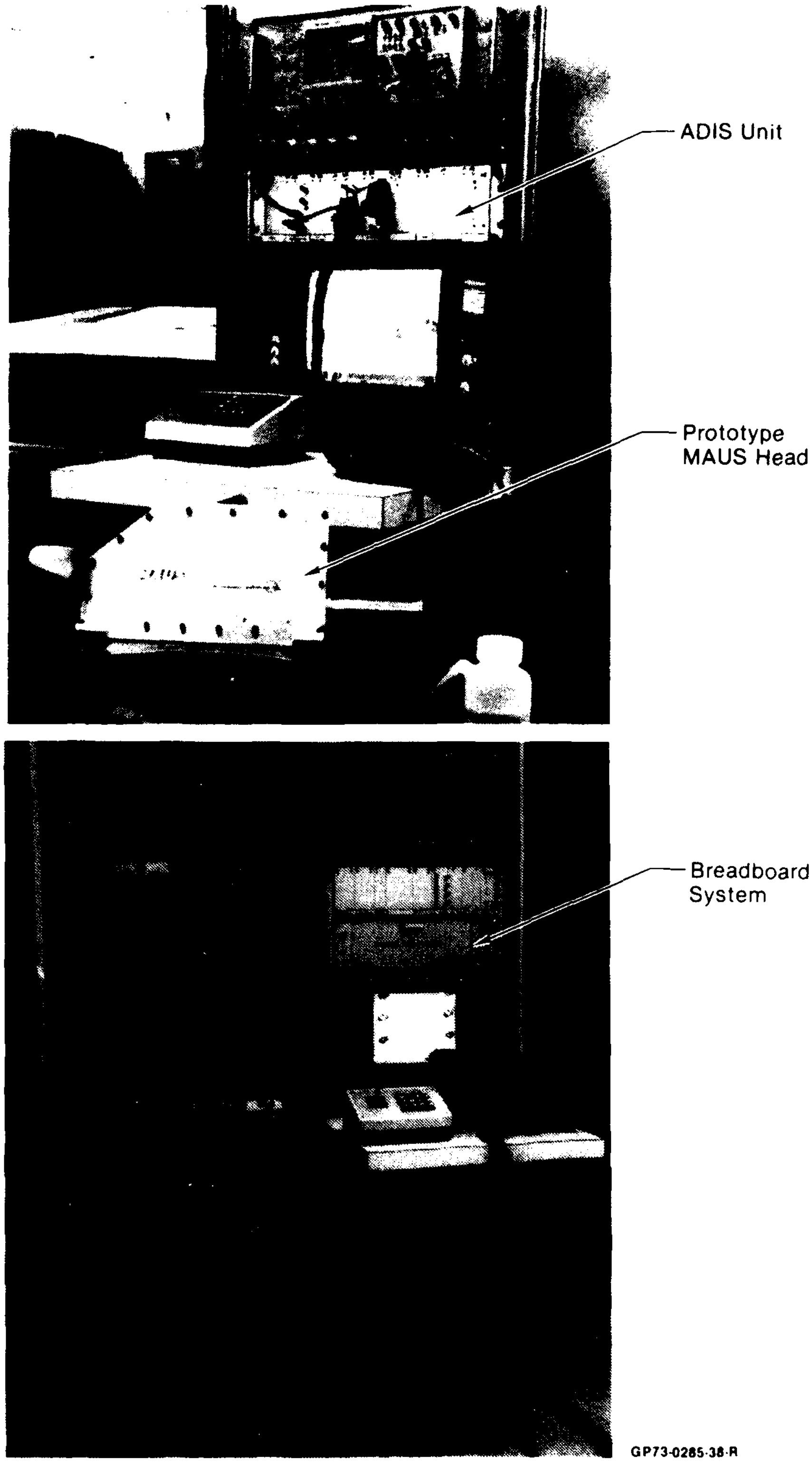


Figure 25. MAUS Development Facilities

2.3.1 Mechanical Scanner Design - Several mechanical scanner concepts were investigated for the large area scanner application. Of those studied the more promising were the original oscillating arm mechanism, the liquid filled bag discussed in Task II sections, and the belt mechanism. The belt configuration shown in Figure 26 was selected for the large area scanner design. The four transducer configuration with an eight inch scan width was selected as a compromise between scanner size and scan speed. For example, the current belt scanner design could be expanded to a sixteen inch width

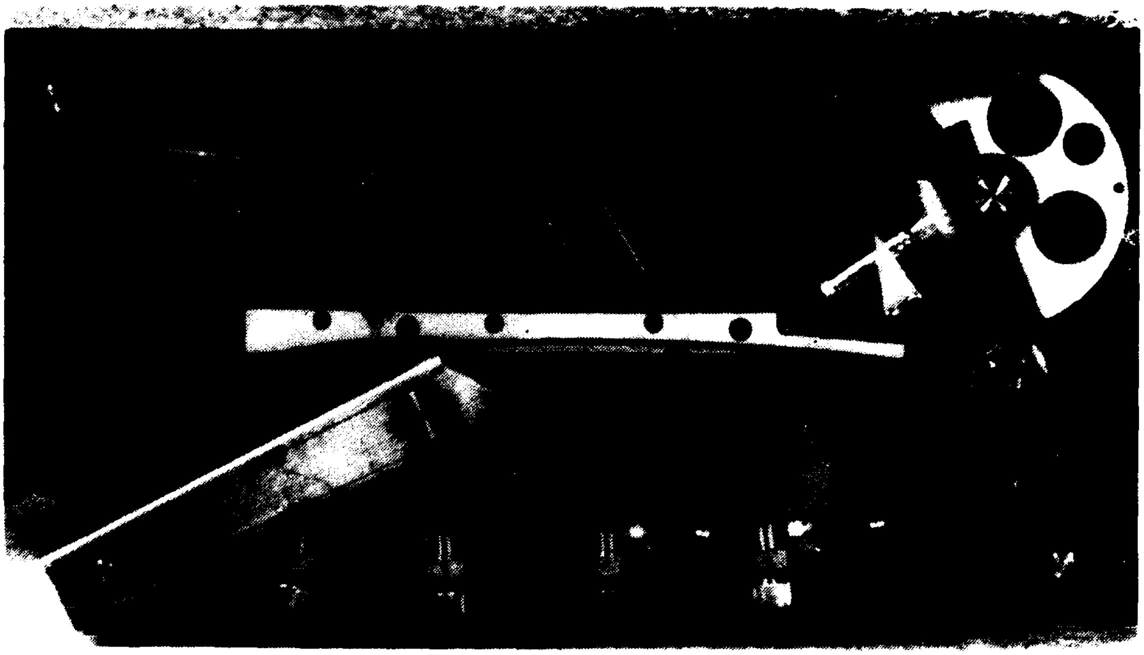


Figure 26. MAUS Scanner GP73-0285-39-R

using eight transducers. This of course would double the weight and increase the allowable radius of curvature in the scan direction. Also a large mechanical scanner cannot be used in confined spaces. Ideally, a number of different sizes and shaped mechanical scanners (and arrays) could be developed for specific inspection needs. These special heads could be made plug compatible and all interface into the same electronic package.

Some of the problems inherent in the first oscillating arm MAUS prototype scanner design have been addressed in the belt scanner development. The problems identified in the first scanner design were; 1) surface distance error in the scan direction due to change in the length of the scanning arms, 2) high construction cost due to the complexity of the mechanical mechanism, and 3) transducer-to-part surface coupling problems. The belt scanner has solved the surface distance error problem and should be cheaper to produce due to the simpler mechanical design. Surface coupling problems do not have a single solution. The belt scanner has a continuous scan surface (Figure 27) with no edges and will retain coupling better on smooth part surfaces. However, the button design used on the first scanner design may have an advantage on surfaces with protruding fasteners. The buttons around the transducer allows it to step over a fasteners without lifting the remaining transducers off the part surface.

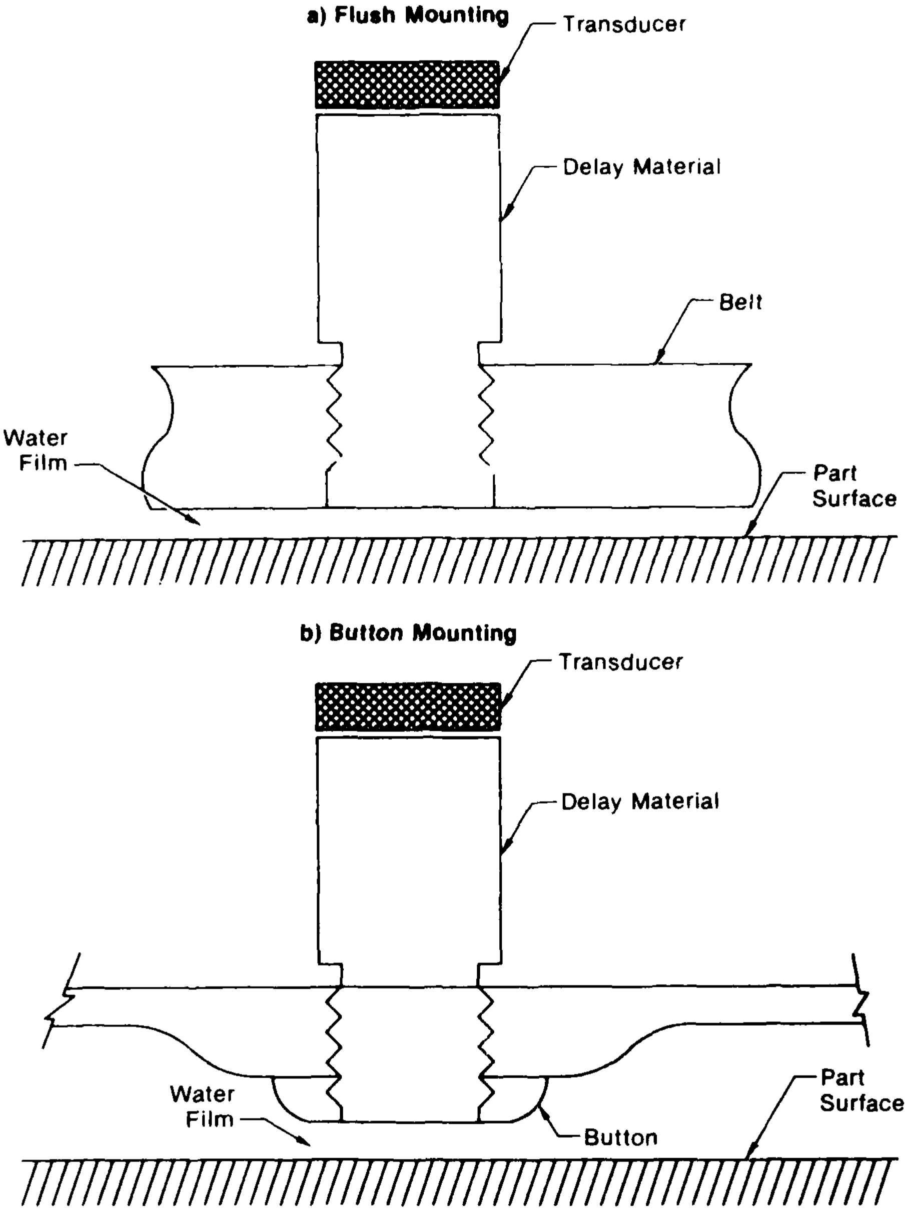


Figure 27. Transducer Mounting

GP73-0285-27

Investigations into delay line materials, couplant, and ultrasonic transducers have been reported in preceeding sections. Both the oscillating arm mechanism and the belt mechanism use standard commercially available transducers which can be easily changed. This is an important feature which allows damaged transducers to be replaced and also makes changing ultrasonic frequency simple.

The upper limit of the MAUS motor driven scanning motion is six to eight cycles per second. This allows a forward scan velocity of one inch per second. With an eight inch scan path, this yields a theoretical inspection rate of two hundred square feet per hour. The ultrasonic data spatial resolution can vary from 0.04 inch by 0.04 inch to 0.16 inch by 0.16 inch., depending on how fast the MAUS is pushed across the part surface. The MAUS software monitors the actual scan speed and automatically adjusts the data pixel size. This feature allows the MAUS to be moved fast to cover large surface areas. The larger pixel size causes some image distortion, but higher resolution image can be achieved by simply slowing down the scan motion, or by back tracking over the image at a slower speed.

Ergnonomic considerations are important for one man operation. Figure 28 is a conceptual drawing of the MAUS Scanner and Electronic Package. The scanner is connected to the electronics chassis by a single cable up to forty feet in length. The switches necessary to acquire ultrasonic image data can be located on the scanner head. The breadboard scanner has only a start scan switch, not the full key pad as shown. The ultrasonic data system set-up parameters are selected prior to scanning. The ultrasonic data system is discussed in the following sections. Once the proper ultrasonic system parameters are selected, the inspection begins by simply pressing the Start Scan key located on the scanner and pushing the scanner across the part. A remote monitor can be attached to the scanner head to provide the operator with a C-scan image of depth information in real time.

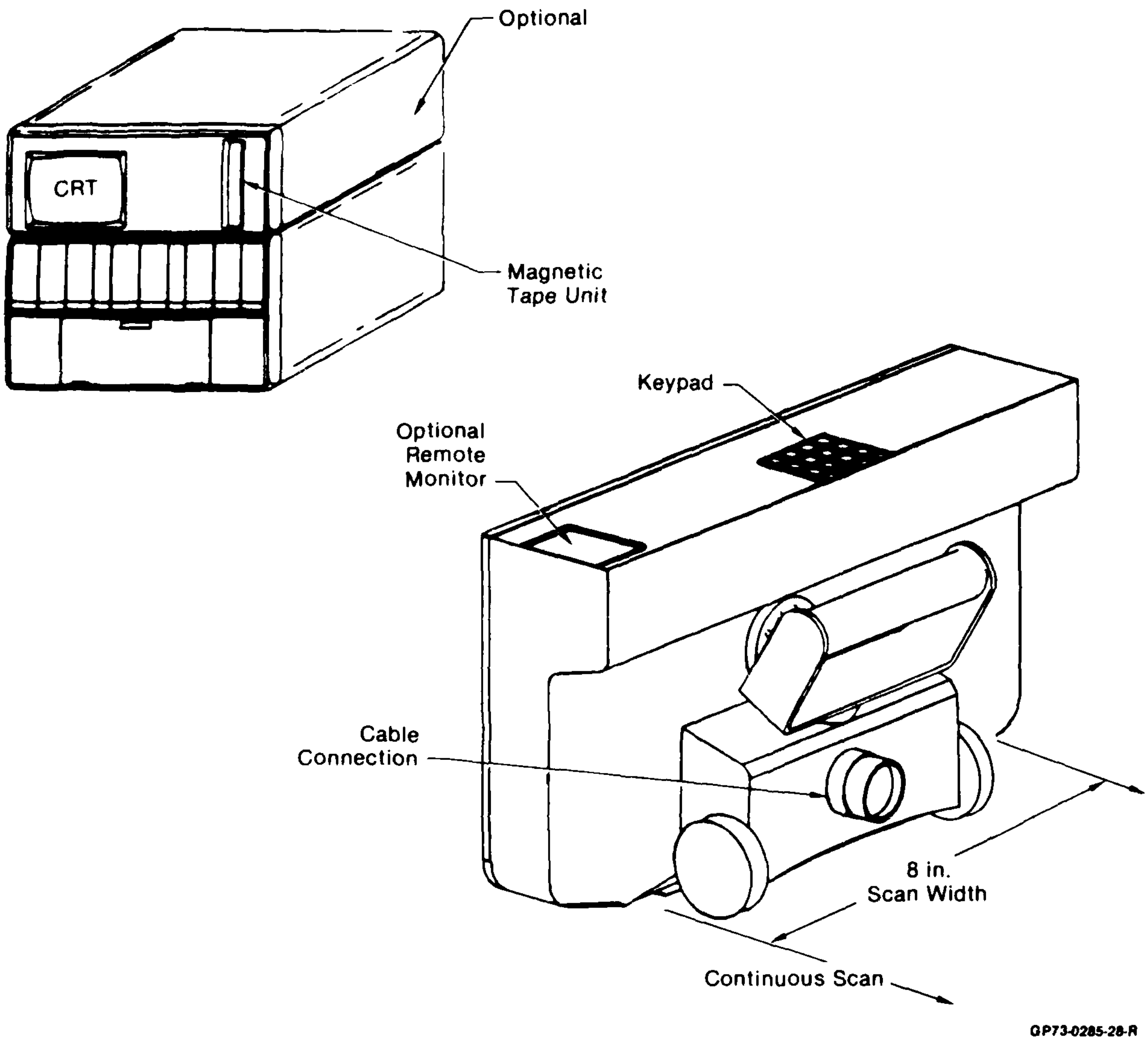


Figure 28. Conceptual MAUS Scanner and Electronics Package

2.3.1.1 Curved Surface Capability - Figure 29 illustrates the flexible belt concept used on the large area scanner MAUS. The scanner consists of four transducers mounted two inches apart on a flexible belt. The belt is oscillated through a two inch region to create a line of inspection that is eight inches wide. The belt will conform to parts that have up to a 30 inch radius of curvature. The curvature can be concave or convex. The belt is spring loaded so that it holds the transducers in contact with and normal to the part at all times.

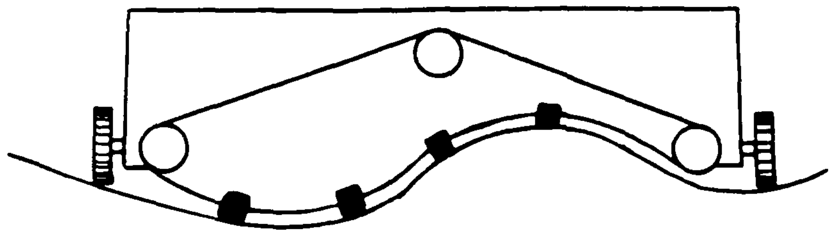


Figure 29. Flexible Belt Concept

The scanner is mounted on wheels so that it can be rolled across the part. The wheels are placed so that the scanner will always keep the transducers normal to the part. The MAUS can follow a 5 inch radius of curvature along the axis of its wheels and a 30 inch radius along the belt. One wheel and the belt position are encoded, so that the ultrasonic transducer positions relative to the part surface are continually being measured as the MAUS is moved across the part surface. The MAUS provides flexibility (Figure 30) in selecting the scan paths across a part. This flexibility allows C-scan images to be rapidly created, even on compound curved surfaces. Since the MAUS actually measures the surface distance in both the scan and index directions, the system unfolds the ultrasonic data so that distortion of the displayed image is minimized. The data is not projected into a flat plane, but is actually unfolded onto a surface which corresponds to the part being scanned.

The MAUS mechanism that has been described can acquire a path of data eight inches wide across a part surface. A simple method has been developed that ensures 100% coverage of large areas. A marking device is attached to the MAUS as shown in Figure 31. As the MAUS is moved across the part, a line is made on the part surface with water soluble ink. The guide line made by the preceeding scan is used to guide the current scan. The reference start line shown is made on the part surface prior to starting the inspection. Other reference lines can be made on the part with tape or some other means. The MAUS distance counter is reset at the start line for each scan across the part. The distance counter is reset to zero each time the start scan switch, located on the scanner, is pressed. The contents of the surface distance counter is stored along with the ultrasonic data as it is acquired. A position on a part surface can then be located by the surface distance from the start line and the number of scan paths from a reference line or part edge.

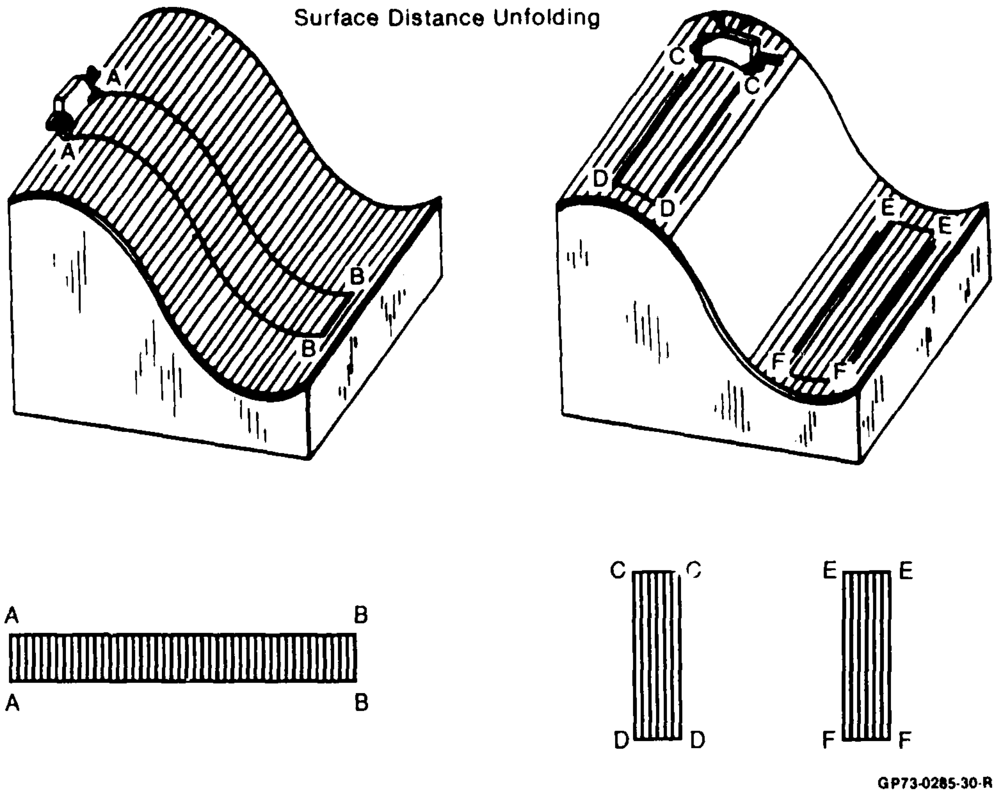


Figure 30. Surface Unfolding

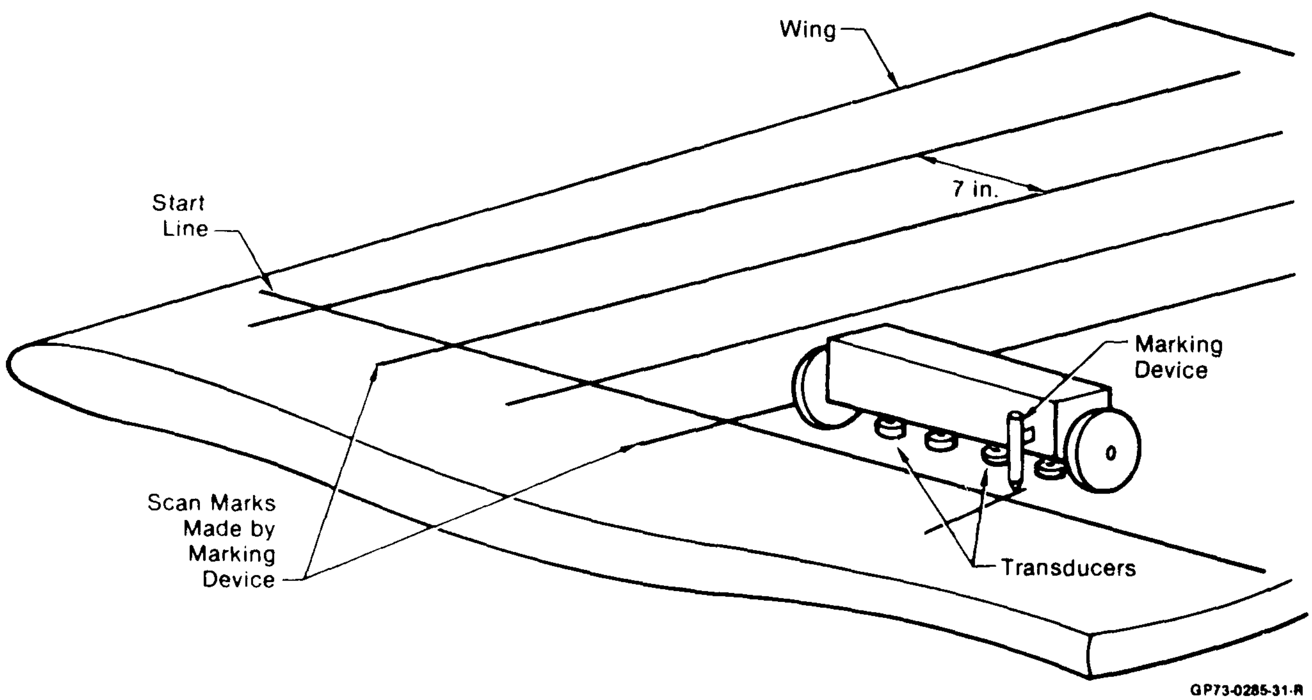


Figure 31. Surface Marking Concept

2.3.2 Ultrasonic Design

2.3.2.1 General System Description - The ultrasonic system used on the MAUS is a MCAIR Ultrasonic Signal Processor (USP) design and is an integral part of the system. This integrated approach provides real time acquisition of four channel ultrasonic data and full menu control of the ultrasonic system. The USP is a microprocessor based data acquisition system capable of extracting a number of parameters from the ultrasonic signal. The parameters are obtained in separate modules, so a custom system can be configured depending on the application. Example parameters are pulse-echo thickness or flaw depth, and pulse echo amplitude for back wall amplitude monitoring. The USP was designed to provide an adaptable, expandable data system for ultrasonic NDT applications. The USP is now in use on MCAIR's AUSS IV, AUSS V, ADIS, and MAUS systems.

The MAUS ultrasonic signals are generated and acquired every 0.040 inches in the oscillating motion direction and are amplified in the Four Channel Pulser Receiver module mounted in the electronics package. The output of the Four Channel Pulser Receiver is a single RF line with the ultrasonic signals from the four transducers multiplexed onto this line. The block diagram of the breadboard system is shown in Figure 32. Table 4 contains the MAUS ultrasonic data system specifications.

2.3.2.2 Pulse-Echo Time-of-Flight Data Acquisition - The MAUS pulse-echo data system acquires data over the 2.25 to 15 MHz frequency range and is capable of acquiring time-of-flight (depth) from a part under test. Pulse-echo depth data is determined by measuring the time between the front surface reflection of the test specimen and the next significant reflection, either the back surface of the test specimen for a thickness measurement, or a flaw for a flaw depth measurement.

To obtain this depth data the RF ultrasonic signal is first run through programmable gain and time corrected gain stages. The programmable gain stage allows the overall gain to be set for each channel to produce detectable signal levels and to account for sensitivity variations between the four transducers. The time corrected gain feature increases the gain as a function of time starting at the front surface. This feature compensates for the increased attenuation of the data signal caused by increasing test specimen thickness. The sensitivity of flaw detection at various levels can thus be normalized. Nine rates of gain increase are available in either a linear or exponential function of time. The start of the gain increase can also be delayed back from the front surface.

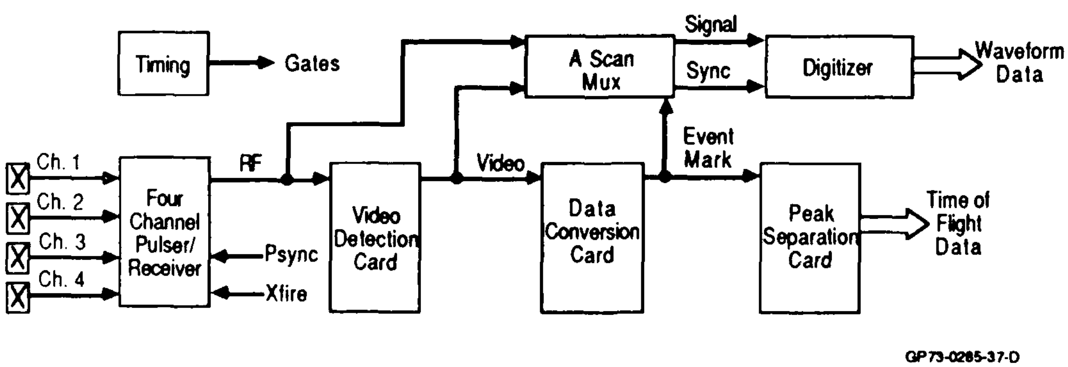


Figure 32. Block Diagram of MAUS Ultrasonic System

Table 4

MAUS ULTRASONIC DATA SYSTEM SPECIFICATIONS

PULSER	
D.C. Excitation Voltage	500 VDC
Peak Voltage into 50 ohms	300 VPK minimum
Rise Time (10 to 90%)	15 nanosec. max.
FOUR CHANNEL PULSER RECEIVER	
Input Impedance	50 ohms
Gain	6 dB
Frequency Response	± 1 dB (0.5-20 MHz)
PULSE-ECHO DEPTH DATA SYSTEM	
Input Dynamic Range (manual or automatic gain control modes)	34 dB
Time Corrected Gain Adjustment Range (nine rates of increase in both linear and exponential modes)	30 dB
Thickness Resolution	20 nanoseconds (0.00125" in carbon/epoxy)
Maximum Thickness	40.8 microseconds (2.55" in carbon/epoxy)
Operating Frequency Range	5 to 20 MHz (wider ranges available on request)
Front Surface Gate	0.02 to 5.12 microseconds (0.02 increments)
SYSTEM GATES (Pulse Echo Depth, Discriminator, TCG Delay)	
Range	0.15 to 255.85 microsec. (0.15 intervals)
Width	0.15 to 255.85 microsec. (0.15 intervals)
Trigger	main bang or first interface

After the gain stages, the RF signal is then full wave detected and filtered into a video waveform. The amount of filtering is programmable to allow for compromises between near surface resolution, transducer frequency and damping, and surface texture. This video signal is routed to the event mark generation card and is also available for display.

The event mark technique uses a differentiator/zero cross detection circuit to produce a digital signal at every peak in the video waveform above a threshold. This event mark signal is then sent to a counter circuit which measures the time between the first two peaks or "events". This time measurement is the pulse echo thickness or flaw depth data.

An important point is that the digital event signal is generated at <u>every peak</u> in the video waveform above the threshold. This gives a true thickness measurement as the individual pulse width does not affect the measurement. This also gives very good near surface resolution, as the video waveform does not have to return below the threshold to generate a second event. In this way near surface resolution of flaws as close as 0.01 inch in carbon/epoxy are detected with a 5 MHz search highly damped search unit. Figure 33 shows typical waveforms for the good and flaw areas of a part. The following Figure 34 shows a more detailed timing diagram of how an event mark is generated.

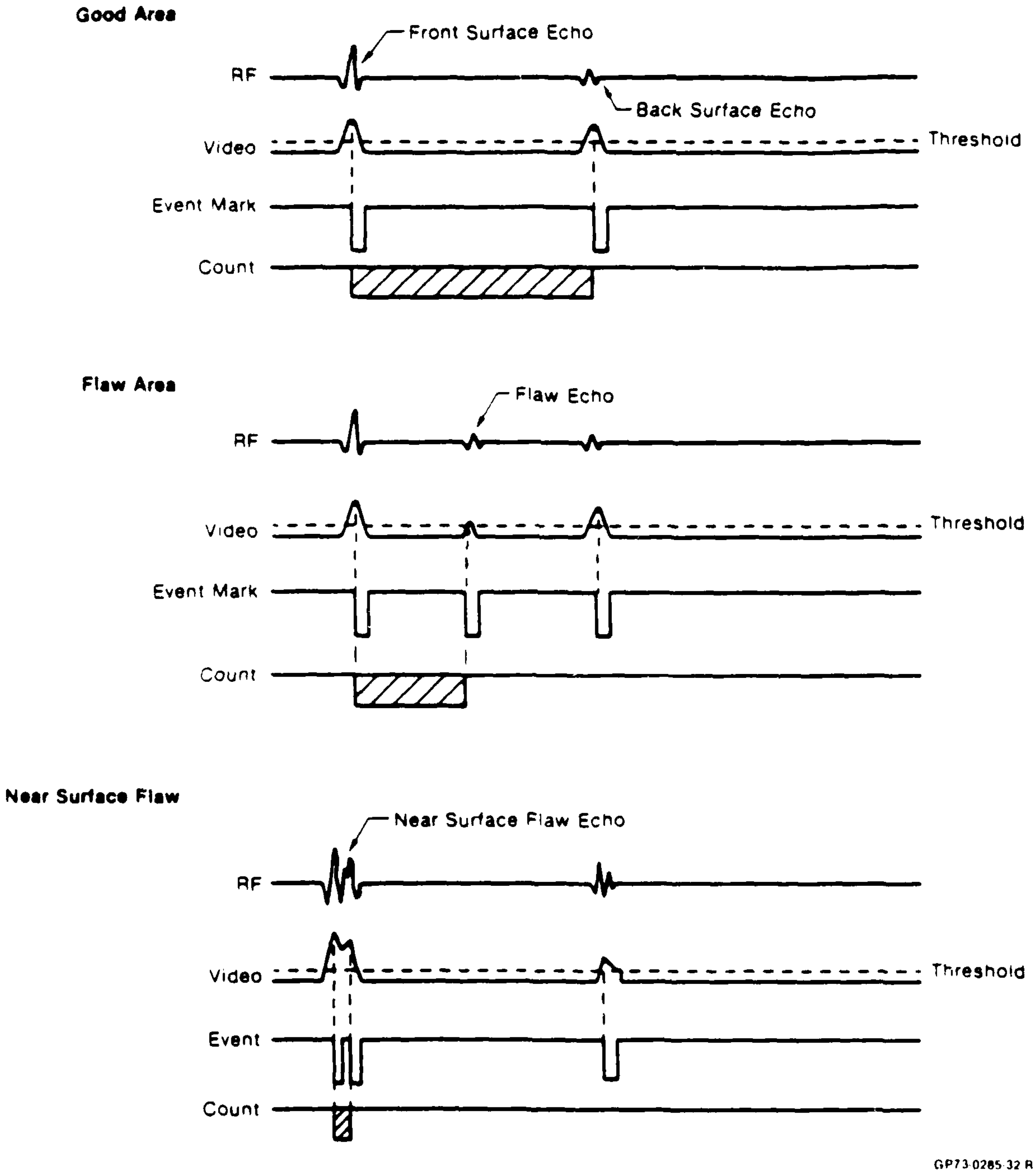


Figure 33. MAUS Pulse-Echo Inspection Waveforms

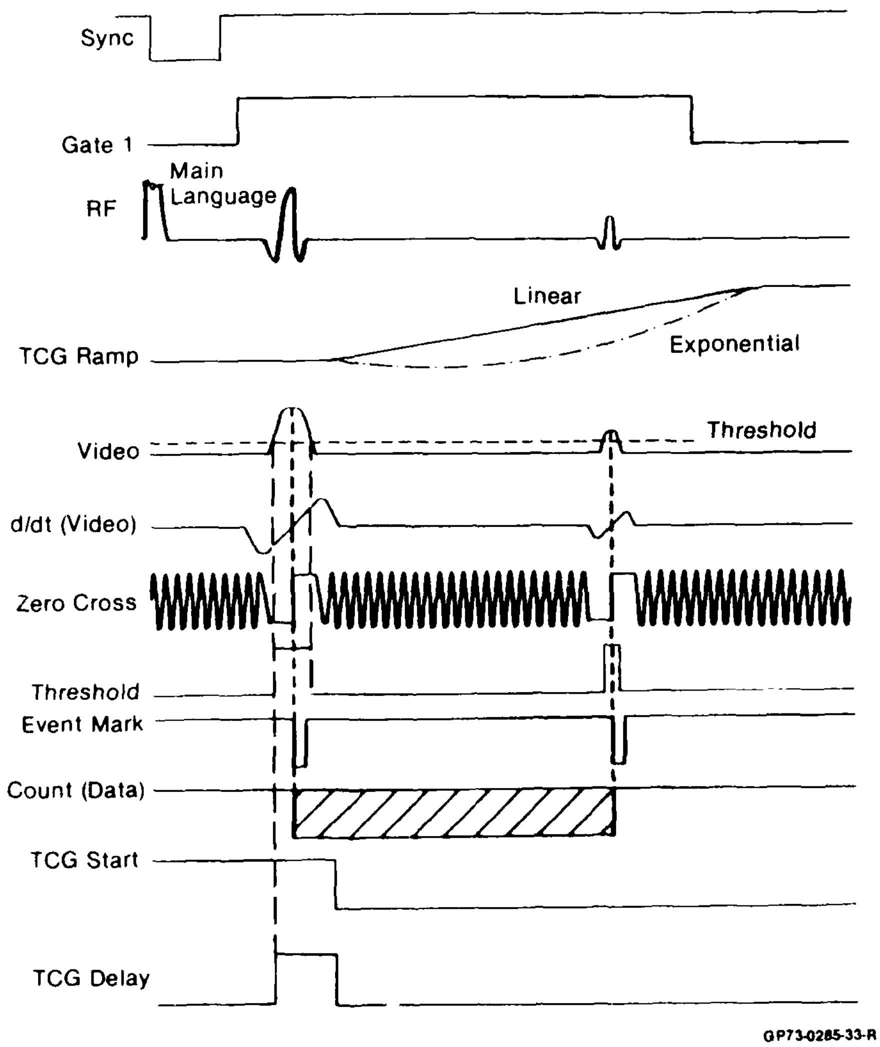


Figure 34. MAUS Pulse-Echo Electronic Signal Waveforms

The MAUS pulse echo depth system requires the mechanical scanner to maintain normality to the part surface within plus or minus two degrees and also to maintain contact with the part surface with sufficient coupling media. Loss of coupling or normality will typically result in a white or out of range thickness reading due to only one reflection being encountered, the end of the delay line.

In the MAUS, the Peak Separation Module measures the actual time increment between the first two events. A 50 MHz clock is used in the timer circuit. Maximum possible resolution (minimum increment) is 0.00125 inch in carbon/epoxy, which corresponds to the 50 MHz clock cycle. At the minimum resolution step and an 8 bit data word, the maximum part thickness inspectable would be 0.319 inch. With 0.005 inch resolution and an 8 bit data word, the maximum part thickness would be 1.28 inches. The resolution step (and therefore maximum thickness) is a programmable option. Maximum thicknesses of 0.32 inch, 0.64 inch, 1.28 inches and 2.55 inches are available.

2.3.2.3 LAS Improvements - In the course of the ultrasonic investigation of the Task I composite parts during Task II, a number of desired improvements to the pulse echo depth system were identified. They are explained in the following paragraphs along with their implementation into the breadboard demonstration system.

Depth Count Out of Range - One of the identified problems was with the counter circuit used to measure the time between the two event marks. A 16 bit counter is used, clocking at 50 MHz starting at the front surface reflection. The MAUS stores data in an 8 bit format, with the desired 8 bits of the 16 bit counter selected by the resolution/maximum thickness desired. A problem occurs when no second event or reflection is encountered within the maximum thickness range selected. The counter then continued to count with the lower 8 bits rolling over and possibly giving erroneous flaw depth or thickness indications. The fix on the LAS demonstration breadboard was to read all 16 bits and, via software, scale to the thickness range desired, with out-of-range values set to give maximum thickness indications.

Time Corrected Gain Delay - The second identified problem was in the time corrected gain circuit. On thick parts such as the F/A-18 inner wing skin with sloping back surfaces, the single slope time corrected gain led to problems with the delay line search unit, though it works well with a focused immersion unit in our large C-scan systems. If the TCG were increased enough to get flaws near a sloped back surface, there would be too much gain in the 0.3 to 0.6 inch deep range leading to false flaw indications. The solution on the MAUS prototype was to implement a potentiometer controlled delay in the start of the TCG slope. A 2.5 microsecond (or 0.16 inches of C/E) delay worked out best for detection of flaws in the F/A-18 inner wing skin. This delay also cleaned up front surface reflections. Apparently the TCG start signal was generating a noise spike that was coupling into the front surface RF signal. The result is that a lower filter setting can now be used to give improved near surface resolution in the 0.010 inch range of carbon/epoxy.

The TCG delay was implemented on the breadboard demonstration system by using one of the five available system gates as a CGA delay gate. Use of the GCA delay gate was implemented by modifying the video detection module. The TCG delay may be turned off or set from 0.50 to 20.0 microseconds in 0.167 microsecond intervals.

Advance Peak Separation Module - The LAS breadboard demonstration system is the first system with the new advanced peak separation module. The module was developed to improve the inspection capabilities of complex structures. New features are a front surface gate, event mark discrimination and qualification, and multiple event mark detection capability. The front surface gate circuit allows the user to gate out events near the surface of the part such as peel ply, paint, or rough surface conditions. It can be set from 0.02 to 5.12 microseconds in 0.02 intervals. This gate must be set carefully to avoid gating out near surface flaw indications. The discriminator circuit allows known reflective interfaces to be gated out inside the part. Examples are fiberglass reinforcing layers or adhesive bondlines. The qualifier circuit allows the operator to look at only a certain area inside the part by only looking at signals inside the qualifier gate. Finally the advance peak separation module allows timing measurements of events other than the normal first to second. First to third and second third measurements are also possible. These alternate measurements are not presently available on the demonstration system menus.

2.3.2.4 Breadboard System Evaluation - The tests performed in Task II, which evaluated the Prototype MAUS effectiveness in detecting the simulated flaws in the sample part, were repeated using the breadboard systems with the improvements previously described in the last section and all flaws were detected.

2.3.3 Overview of the Breadboard System Operation and Capabilities - The breadboard system's features and its operator interface are described in this section. As previously stated, the LAS has been developed using three systems; the Prototype MAUS, the MAUS Development Station, and an ADIS system.

2.3.3.1 Scan Setup - To get consistent and repeatable inspection data, the ultrasonic instrument must be capable of storing and retrieving setup information. However, to determine the setup parameters the system must also be able to operate in a mode similar to a conventional flaw detector. The LAS allows the operator to choose between three different setup methods: Manual Data System, Automatic Data System, and Store/Recall scan. Each of these methods require progressively less expertise in setting up the ultrasonic instrument.

The Manual Data System is a menu on the MAUS system. At the top of the screen an A-scan trace of the ultrasonic signal is displayed, as well as the ultrasonic gates, see Figure 35. In this menu, direct control is available over all of the ultrasonic signal processor's triggers, gates, gains, filters, and thresholds. As the settings are changed the operator can see on the display how the adjustments are affecting the ultrasonic signal. However, because it is in a menu, and there are no knobs or switches, these settings can be stored and recalled. The Manual Data System can be used by an experienced operator to get very fine control over the ultrasonics.

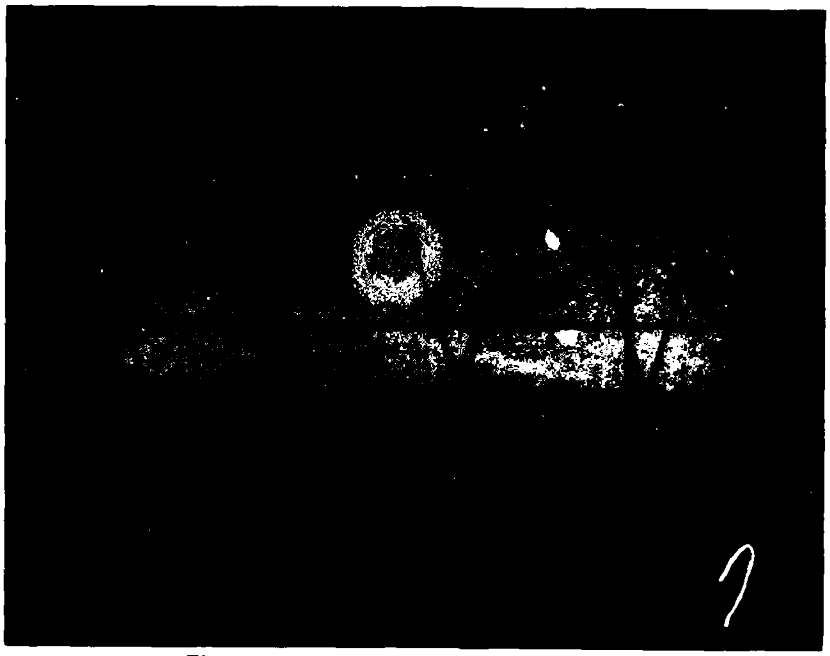


Figure 35. MAUS A-Scan Presentation GP73 0285 40 R

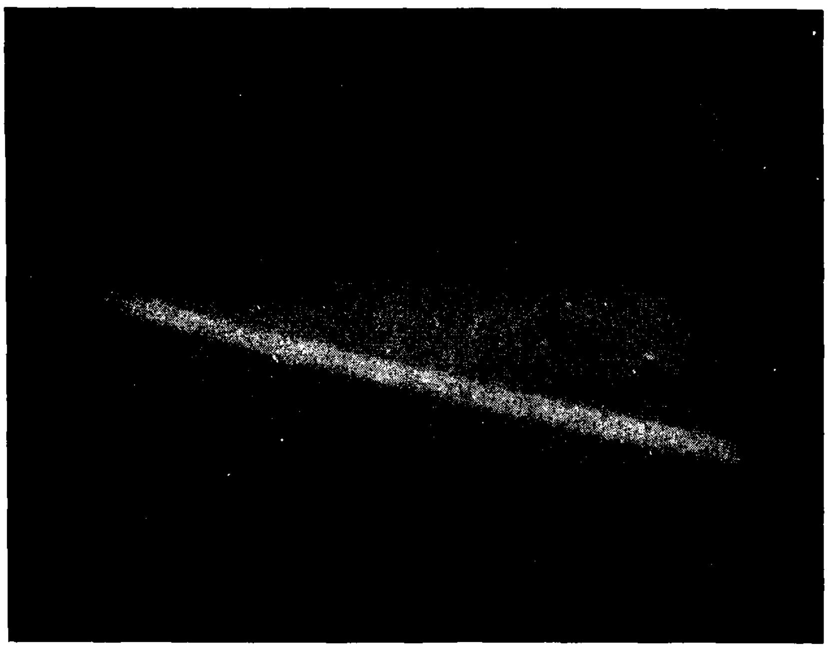
The MAUS provides a simpler method to set up the ultrasonics. This method is provided in the Automated Data System menu. In this menu, information is entered about the part to be inspected: material, structure, and thickness. The MAUS system will automatically generate ultrasonic settings that can be used to scan the part. The operator needs to know some basic information about the part to set up the scan, but no knowledge about the operational details of the ultrasonic signal processor is required.

The simplest method available to set up the ultrasonic signal processor on the MAUS is to recall scan descriptions that have already been stored in non-volatile memory. Any ultrasonic setup that the operator creates can be stored under a name that the operator enters. The MAUS can store up to 30 scan descriptions. These scan descriptions can then be recalled by name and will be loaded into the ultrasonic signal processor. This feature can be used to save setup time when a large number of aircraft must be inspected.

These three methods can be used in concert in order to get more consistent inspection results among all operators. An expert operator can use the Automatic Data System menu to get an initial scan description for a particular assembly, then the expert operator can fine tune the ultrasonic signal processor, using the Manual Data System menu, to get the best inspection results. This description can then be saved under a name. Every operator could then scan the assembly using the same scan description. Therefore, the three methods of ultrasonic setup on the MAUS combine to minimize the differences between operators.

2.3.3.2 Operator Interface - The operator interface for the LAS has been developed using the MAUS Development Station. It has been implemented so that it can be used in two ways. The simplest way involves the use of just one button: Start Scan. The MAUS loads the ultrasonic signal processor with the values that were last used, and the system is immediately ready to scan. The screen is filled with ultrasonic data as the inspector pushes the MAUS across the part.

The MAUS also has a full set of menus through which the inspector can use its advanced features. These menus are simple to use. The menus have been laid out in a well organized hierarchy so that keystrokes have been minimized. The inspector uses just a few keys to move the cursor about and make selections in the menus. No wrong entries can be made because the value for each item in the menu is selected from a list that the operator rolls through using the value control keys. Help messages are available on all menus. Figure 36 shows a typical message. These messages explain the purpose of the menu, describe each item in the menu, and list the possible values each item in the menu can assume.



GP73-0285-41-R

Figure 36. Typical MAUS Help Message

2.3.3.3 Data Analysis - The display on the MAUS is a graphics screen with 256 pixels by 240 pixels. Each pixel represents a cell on the part that is .04" by .04". Therefore the screen displays data for an area of about ten inches by eight inches. The remaining area at the bottom of the screen is used to display a legend. This legend is selected by the inspector. Different legend modes are available to enhance the data display.

The simplest legend is just a color bar and a numeric display of the current mapping limits. These mapping limits are used to distribute the palette of colors and gray shades over the data. The MAUS displays data in 200 shades of gray or color. The imaging system can distribute the 200 shades over the entire range of data, or the shades can be concentrated on just a smaller range of data to create more contrast. This method of remapping the shades of gray over the full range of ultrasonic data is sometimes referred to as "electronic rescan," because simple threshold systems used to require that parts be physically rescanned in order to do what is now accomplished with electronics and full range data.

The MAUS can also display the data in color. The color palette has been randomized so that data values that are only one level apart are displayed as very different colors. This provides high contrast for a quick overview of the data; areas that have just a slightly different data value from their surroundings can be enhanced in color and then done in shades of gray using the remapping feature.

The MAUS provides another legend called the Gauging Mode. In this legend two cursors can be moved about on the data image. At the bottom of the screen, the thickness under each cursor is displayed in inches, as well as the distance between the two cursors. These three numbers are continually updated. This legend mode can be used to determine the exact size and depth of a flaw. It also provides a means of locating that flaw in relation to reference features on the part.

The MAUS system provides another legend called the Cross-Section Mode. In this legend the cursor keys move a line that is selected to be either vertical or horizontal. This line represents where the inspector wants to get a cross section of the part. When the execute key is pressed, a cross-section B-scan of the part through that line is displayed on the screen. This is good way to get a visual picture of the depth of a flaw with reference to the front and back surfaces of the part.

To locate the position of scanner with respect to the point where the start scan switch was pushed, a ruler legend is provided. In the ruler mode a scale and position indicator is displayed. This is used to locate the position of features being displayed. A method of marking the part while scanning is discussed in Section 2.3.1.1.

To annotate the image displayed on the CRT, an annotation legend is provided, see Figure 37. The annotation mode allows the user to enter ASCII text to be displayed over the image data. The text is entered using the cursor to select alpha-numeric characters displayed on the CRT.

GP73-0285-42 R

Figure 37. Example of MAUS Screen Annotation Capability

2.3.3.4 Data Archiving - Data archiving is used to save data as it is acquired so that it can be analyzed at a later time and also to recall previous inspection results to compare it to the current data to track problems on aircraft. The ADIS demonstration system can store 300 square feet of part data on a 30 Megabyte magnetic disk. Storage capacity can be optionally expandable. An interface for a magnetic tape cartridge system has also been developed. The tape system allows the archival storage of any part data on the magnetic disk. Data can be stored in real time on the magnetic disk and then at a later time, be archivally stored on the cartridge tape drive.

The MAUS Development Station did not have a tape storage system. The design plans for the system would allow the data to be stored first in video display memory then streamed out to a cartridge tape drive.

Ultrasonic data can also be archived to a plotter. Data can be plotted in 16 simulated shades of gray at 10 square inches per second with 2500 picture elements per square inch. Each plot begins with a header page containing all the information on how the part was scanned.

3.0 CONCLUSIONS AND RECOMMENDATIONS

During the course of the program, all major tasks identified in the statements of work have been successfully completed. These tasks have included the following:

- Fabrication of composite structural demonstration panels with simulated flaws
- Development of a large area composite rapid scanning NDE technique
- Rapid scanning detection and delineation of delamination/debonds of two square inches or greater in carbon/epoxy composite laminates
- Front and back surface rapid scanning first flaw discontinuity detection with a resolution to +/- 2 plies (C.25 inch minimum skin thickness) to +/- 5% of thickness (at maximum of 2 inch thickness)
- Flaw location mapping for hard copy reproduction and CRT display to within a 1/2 inch by 1/2 inch grid resolution
- Rapid scanning inspection speed greater than 100 square feet per hour
- Curved surface inspection capability of a 36 inch radius in the direction perpendicular to the scan axis and less than a 5 inch radius in the scan direction
- Data storage of inspection results, scan information, set-up parameters, part and flaw identification/annotation features, and C-scan presentation capabilities
- Assembly, evaluation, and demonstration of breadboard system

The results of the program indicate that rapid large area composite scanning is possible by utilizing a MAUS or reciprocating ultrasonic pulse-echo time-of-flight technique and data acquisition. This type of system is capable of detecting in-service flaws of 2.0 square inches or greater at a minimum scan rate of 100 square feet per hour, and appears to provide production type images and C-scan presentations at comparable production inspection speeds. The operator interface scan start or menu driven USP loading simplifies set-up time and minimizes the use of a reference standard. As a result, required training and skill levels are kept to a minimum. In addition, the scan head of the breadboard system weighs only 7 pounds and the electronics can be repackaged into a portable two component system. This electronic and physical combination provides a cost effective approach to in-service inspection of large area composite laminates. The current breadboard system and scanner head represent a viable inspection tool for immediate applications.

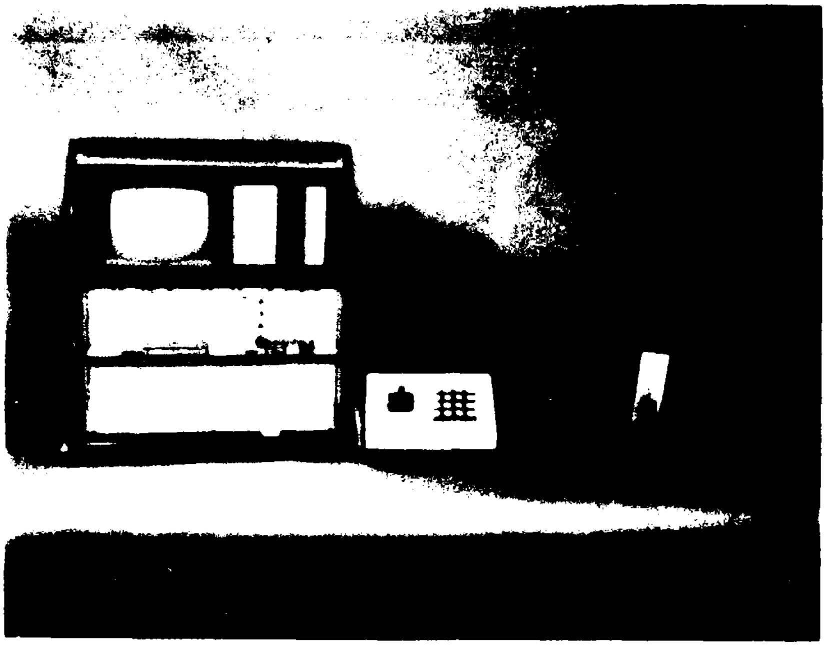
The feasibility of the reciprocating type ultrasonic scanner concept has been proven, but there are areas of where additional developments could improve system performance and reliability. These activities would include improvements in the scanner and electronic data acquisition area.

Even though the breadboard scan head weighs only 7 pounds, scanning overhead lower mold line surfaces may become tedious and tiring. The lightest system available will be desired for overhead handheld or automated scanning. Scanner head weight reduction will be a necessity. Potential weight reduction includes a redesign and the use of a plastic housing on the existing scan head. The development of smaller mechanical scanners and small handheld arrays will also reduce the effort required for overhead scanning.

Improvements in sound coupling should provide improved data acquisition accuracy, detection sensitivity, imaging, and belt wear reliability. The button type prototype scanner proved effective on flat upper surfaces, but had limitations on lower and vertical surfaces because of sound coupling inconsistencies. The belt type system and water liquid used with the breadboard scan head appears to provide consistent and adequate coupling during upper, lower, or vertical scanning. In addition, speed control and the use of a teflon impregnated belt have reduced part-to-surface friction and improved transducer velocity consistency. These coupling and velocity effects should be optimized for improved sound coupling characteristics and belt wear reliability. The bag type scanner, proven feasible for use on thick laminates, could be developed and should provide superior coupling and wear reliability. Improvements in air coupling transducers or methods that eliminate liquid media represent ideal inspection systems, and need to be implemented when the technology is developed.

Electronically, the large area composite scanner has incorporated many user friendly and sophisticated data acquisition features. Developments, that may improve ergonomics, sensitivity, and reliability, include designing for field supportability and supplemental pulse-echo amplitude data acquisition. The breadboard system has been repackaged into the unit shown in Figure 38. The USP, supporting scanner electronics, CRT, tape drive data storage system, and MAUS scanner head have the equivalent capability of the breadboard system. Even though this system demonstrates downsizing potential, additional repackaging is needed to enhance portability and ruggedness. Additionally, acquired data features, which could provide information on detected flaw features, include back surface tracking and multiple interface pulse-echo amplitude information. Future considerations feasible for incorporation include modem interface for off-site data transmission and the use of artificial intelligence for determination of set-up parameters and image evaluation.

In summary, this effort has demonstrated that reciprocating ultrasonic pulse-echo time-of-flight inspection is a feasible method for flaw imaging in composite laminate structures. This technique allows large area surfaces to be scanned at rates that exceed 100 square feet per hour and detect flaws of 2 square inches at +/- 2 plies in 0.25 inch thick or +/- 5% of the thickness in laminates up to 2 inches thick. Data acquisition and storage allow CRT flaw sizing, depth determination, annotation, and C-scan presentation information to be evaluated in the near real time or stored for off-site interrogation and hard copy printing. System set-up, operator interface, and USP loading are menu driven and require minimum training and skill to operate. The breadboard inpection system is currently a viable NDE tool, but system sensitivity, reliability, and field supportability may be improved by developing a light weight scanner, ensuring consistent coupling or eliminating the need for a contact coupling, repackaging for portability and ruggedness, and investigating the significance and use of pulse-echo amplitude data.



GP73-0285-43-R

Figure 38. Portable MAUS Inspection System

REFERENCES

(1) N. M. Bhatia, "Impact Damage Tolerance of Thick Graphite Epoxy Laminates," Report No. NADC-79038-60, NADC, Warminster, PA 18974, January 1979.

(2) Tsao, M.C., Grills, R.H., Simpson, R.R., "Ultrasonic Imaging Analysis of Component Integrity," "Review of Progress in Quantitative Nondestructive Evaluation," V3A, Plenum Press, New York, pp. 459-466, 1984.

(3) Chang, F.H. In-service Composite Inspection System Producibility, Report AFWAL-TR-84-4101, Air Force Materials Lab, Dayton, OH, August 1984.

(4) B. Jacobs, Composites Inservice Inspection System Producibility, Interim Technical Report. No. IR-205-3(111), Air Force Materials Lab, Dayton, OH, November 1984 to February 1985.

(5) T. Harrington, "A Portable Imaging System for Graphite-Epoxy Composites," Proceedings of the Second DoD/NASA Composite Repair Technology Workshop, Vol. I, pp.285-291, San Diego, November 1986.

(6) T. S. Jones, "Inspection of Composites Using the Automated Ultrasonic Scanning System (AUSS)," Materials Evaluation, Vol. 43, No. 6, May 1985, pp. 746-753.

U S Government Printing Office 1988 548 054/80628

END
DATE
FILMED
5-88
DTIC